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Assessment of wind energy in Iran: A review

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ABSTRACT

In this study, a ten minute period measuring wind speed data for year 2007 at 10 m, 30 m and 40 m heights for different places in Iran, has been statistically analyzed to determine the potential of wind power generation. Sixty eight sites have been studied. The objective is to evaluate the most important characteristics of wind energy in the studied sites. The statistical attitudes permit us to estimate the mean wind speed, the wind speed distribution function, the mean wind power density and the wind rose in the site at three different heights. Some local phenomena are also considered in the characterization of the site.

Contents

1. Introduction

Before the industrial revolution, our energy needs were the modest. For heat, we relied on the sun and burned wood, straw, and dried dung when the sun failed us. For transportation, the muscle of horses and the power of the wind in our sails took us to every corner of the world. For work, we used animals to do jobs that we could not do with our own labor. Water and wind drove the simple machines that ground our grain and pumped our water.

Simple machines based on the ability to harness the power of steam have been found by some sources to date back to ancient Alexandria. The evolution of the steam engine continued over time and significantly ramped up in the 17th and 18th centuries. However, it was the significant adaptations of Thomas Newcomen and

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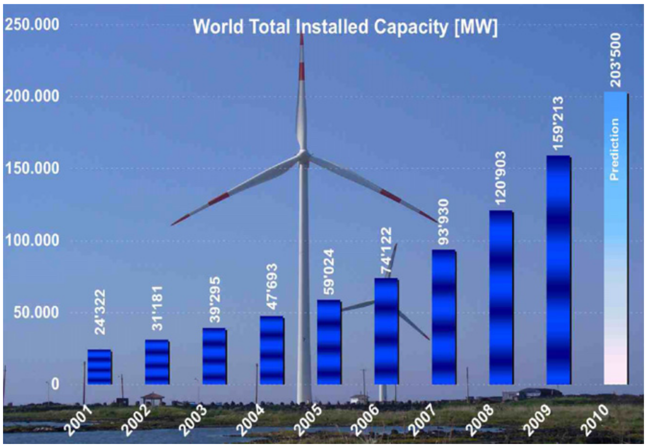


Fig. 1. Development of world wind energy [2].

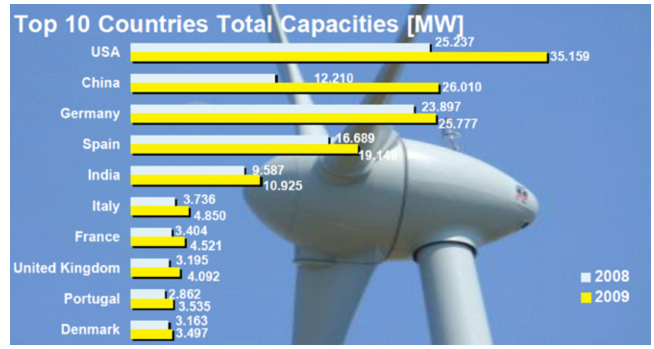


Fig. 2. Top ten countries on usage wind energy [2].

James Watt in the mid-1700s that gave birth to the modern steam engine, opening up a world of the possibility.

More convenient than wind and water and less expensive than a stable full of horses, steam engines soon powered locomotives, factories, and farm implements. Coal was also used for heating buildings and smelting iron into steel. In 1880, coal powered a steam engine attached to the world's first electric generator. Only a year later, the world's first hydroelectric plant went on-line in Appleton, Wisconsin.

With the low-cost automobile and the spread of electricity, our society's use of energy changed forever. Power plants became larger and larger, until we had massive coal plants and hydroelectric dams. Power lines were extended hundreds of miles between cities, bringing electricity to rural areas during the Great Depression. The cheap car made suburbs possible, which in turn made cheap cars necessary, feeding the cycle of suburban sprawl. Energy use grew quickly, doubling every 10 years. The cost of energy production was declining steadily, and the efficient use of energy was simply not a concern.

After World War II unleashed nuclear power, the government looked for a home for "the peaceful atom." They found it in electricity production. Over 200 nuclear power plants were planned across the country, and homes were built with all-electric heating systems to take advantage of this power that would be "too cheap to meter."

In 1973, American support for Israel in the Arab-Israeli War led the Arab oil-producing nations to stop supplying oil to the United States and other western nations. Overnight, oil prices tripled. In 1979, oil prices leaped again, rising 150 percent in a matter of weeks.

During the crisis of energy, the governments of industrial countries were forced to think about the use of renewable energies, such as solar, wind, geothermal and Biomass. With this crisis, a new phase of energies usage was appeared. Solar energy is the primary source of any energy in the world. All of these clean energies come from solar energy.

1.1. Renewable energies

In this section, we will discuss the renewable and clean energies. Renewable energies are generated from natural resources, which are renewable (naturally replenished). In their various forms, they derive directly from the sun, or from heat generated deep in the earth. Included in the definition are electricity and heat generated from solar, wind, ocean, hydropower, biomass, geothermal resources and biofuels, and hydrogen derived from renewable resources. While there are many large-scale renewable energy projects and production/renewable technologies are also suited to small off–grid applications, sometimes in rural and remote areas, energy is often crucial in human development. Some renewable energy technologies are criticized for being intermittent or unsightly, yet the market is growing for many forms of renewable energy.

As mentioned above, solar energy is the basic source of energies such as oil, coal, wind and geothermal. Solar energy is the greatest source of energy for the earth. Solar energy is clean, renewal and accessible all over the world. Fossil resources limitation and environmental changes make solar energy feasible in comparison with fossil fuels, especially in regions with high solar radiation.

Solar energy can be applied in many ways, such as:

1. Generate electricity using photovoltaic solar cells;
2. Generate hydrogen using photo electrochemical cells;
3. Heat and cool air through the use of solar chimneys;
4. Heat water or air for domestic hot water and space heating needs using solar-thermal panels.

Another kind of clean energy is geothermal energy. This energy was obtained by tapping the heat of the earth itself, usually from kilometers deep in the Earth's crust. It is expensive to build a power station, but operating costs are low resulting in low energy costs for suitable sites. Ultimately, this energy derives from the heat in the Earth's core.

The geothermal energy from the core of the earth is closer to the surface in some areas than in others. Where hot underground steam or water can be tapped and brought to the surface, it may be used to generate electricity. Such geothermal power sources exist in certain geologically unstable parts of the world such as Chile, Iceland, New Zealand, United States, the Philippines and Italy.

Another type of renewable energies is Biomass, which is often called "bioenergy" or "biofuels" and is produced from organic materials, either directly from plants or indirectly from industrial, commercial, domestic or agricultural products. It falls into two categories, woody and non-woody biomass. Biomass is considered to be a carbon neutral fuel that can also contribute to waste management. Biomass does not release carbon dioxide to the atmosphere as it absorbs the same amount of carbon when consumed as a fuel. Its advantage is that it can be used to generate electricity with the same equipment as power plants that are now burning fossil fuels. Biomass is an important source of energy and the most important fuel worldwide after coal, oil and natural gas.

Wind energy is the kinetic energy associated with the movement of atmosphere air. It has been used for hundreds of years for sailing, grinding grain, and for irrigation. Wind energy systems convert this kinetic energy to more useful forms of power. These systems have been used for irrigation and milling since ancient times and since the beginning of the 20th century it has been used

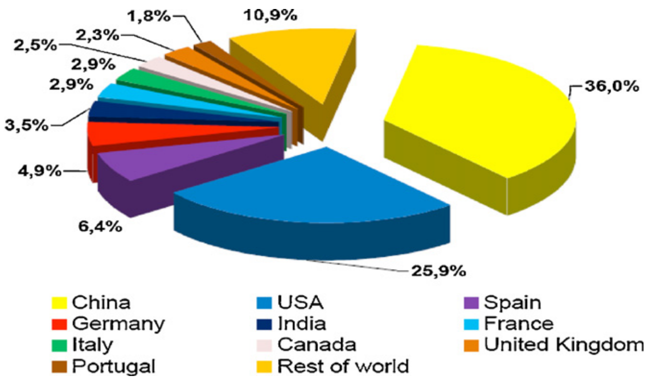


Fig. 3. Country share of new capacity [2].

Table 1
Guide of Iran map.

1. Tehran	2. Qom
3. Markazi	4. Qazvin
5. Gilan	6. Ardabil
7. Zanjan	8. East Azarbaijan
9. West Azarbaijan	10. Kurdistan
11. Hamadan	12. Kermanshah
13. Ilam	14. Lorestan
15. Khuzestan	16. Chahar Mahaal and Bakhtiari
17. Kohkiluyeh and Buyer Ahmad	18. Bushehr
19. Fars	20. Hormozgan
21. Sistan and Baluchistan	22. Kerman
23. Yazd	24. Isfahan
25. Semnan	26. Mazandaran
27. Golestan	28. North Khorasan
29. Razavi Khorasan	30. South Khorasan

to generate electric power. Wind mills have been installed for water pumping in many countries, especially in the rural areas. The power output of a wind turbine running with air flows is a function of the cube of the wind speed, so as wind speed increases, power output increases dramatically, too. Areas where winds are stronger and more constant, such as offshore and high altitude sites, are preferred locations for wind farms.

As early as 5000 B.C., people traveled along the Nile River with boats propelled by wind energy. By 200 B.C., water was being pumped by simple windmills in China, while grain was being grinded by vertical-axis windmills with woven reed sails in Persia. Windmills were being used extensively in the Middle East for food production by the 11th century, which then influenced merchants and crusaders to carry this idea back to Europe.

The Dutch adapted a new method of the windmill and used it to drain lakes and marshes in the Rhine River Delta. In the late 19th century, this technology was brought to the New World by settlers

Fig. 4. The Manjil wind farm [3].

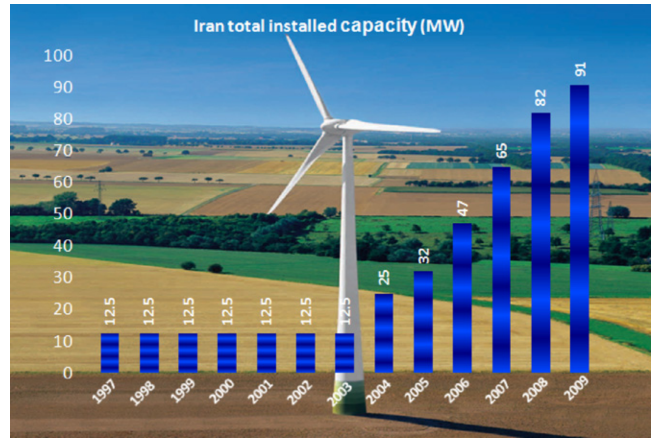


Fig. 5. Growth of wind energy in Iran [10].

who then pumped water to farms and ranches and later generated electricity for homes and industry. In Europe and next in America, industrialization led a steady decline in the use of windmills. However, it also sparked the development of larger windmills in order to generate electricity. These windmills became known as wind turbines, which appeared in Denmark as early as 1890.

At the beginning of the twentieth century, electricity came into use and windmills gradually became wind turbines as the rotor was connected to an electric generator. The first electrical grids consisted of low voltage DC cables with high loss electricity; therefore, they had to be generated close to the site of use. On farms, small wind turbines were ideal for this purpose and in Denmark Poul la Cour, who was among the first to connect a windmill to a generator, gave a course for agricultural electricians. Gradually, however, diesel engines and steam turbines took over the production of electricity and only during the two world wars, when the supply of fuel was scarce, did wind power flourish again. However, even after the Second World War, the development of more efficient wind turbines was still pursued in several countries such as Germany, the US, France, the UK and Denmark [1].

Electricity produced from the wind produces no CO_2 emissions, and therefore does not contribute to the greenhouse effect. Wind energy is proportionately labor intensive and thus makes many

Fig. 6. Provinces of Iran.

Table 2
Location of meteorological sites for analysis [3].

	Site	Province	N(Degree)	E(Degree)
1	Meshkin Shahr	Ardabil	38.40	47.65
2	Namin		38.37	48.37
3	Ahar	East-Azarbaijan	38.58	47.22
4	Bonab		37.40	46.02
5	Mayan		38.08	46.04
6	Oscoo		37.91	46.14
7	Chaldoran	West-Azarbaijan	39.05	44.45
8	Brojen	Isfahan	31.97	51.31
9	Moghar		33.57	52.18
10	Morchekhort		33.10	51.47
11	Varzaneh		32.46	52.61
12	Eshtehard	Tehran	35.72	50.37
13	Latman		35.67	51.42
14	Kahrizak		35.34	51.63
15	Khomeyn	Markazi	33.79	50.16
16	Nahavand	Hamedan	34.26	48.20
17	Rasul Abad		34.83	48.21
18	Kabodarahang		35.34	48.74
19	Delvar	Bushehr	28.83	51.04
20	Bardkhoon		27.98	51.49
21	Esfarayen	North-Khorasan	37.08	57.50
22	Bojnurd		37.47	57.32
23	Davarzan	Razavi-Khorasan	36.26	56.81
24	Sarakhs		36.31	61.14
25	Ghadamgah		36.05	59.00
26	Jangal		37.70	59.20
27	Rudab		35.61	57.30
28	Afriz		34.44	58.96
29	Khaf		34.58	60.16
30	Fadashk	South-Khorasan	32.78	58.78
31	Nehbandan		31.56	60.07
32	Mahi Dasht	Kermanshah	34.26	46.79
33	Divandare	Kordestan	35.97	47.04
34	Ghorve		35.15	47.80
35	Javim	Fars	28.19	54.08
36	Marvdasht		29.98	52.92
37	Abade		31.09	52.25
38	Eghlid		30.88	52.61
39	Rafsanjan	Kerman	30.32	56.22
40	Arzooye		28.43	56.37
41	Shahre Babak		30.09	55.21
42	Kish	Hormozgan	26.32	54.01
43	Jask		25.66	57.72
44	Agh Ghala	Golestan	37.10	54.47
45	Marave Tappe		37.89	55.71
46	Behabad	Yazd	31.77	56.11
47	Ardakan		32.59	54.26
48	Abarkuh		31.30	53.66
49	Korit		33.48	56.94
50	Halvan		33.96	56.29
51	Delgan	Sistan and Baluchistan	27.48	59.45
52	Dehak		27.17	62.55
53	Nosrat Abad		29.81	60.15
54	Chabahar		25.29	60.63
55	Khash		28.09	61.06
56	Lutak		30.77	61.42
57	Langrood	Gilan	37.25	50.23
58	Kahak	Semnan	35.14	52.32
59	Moalleman		34.86	54.57
60	Haddadeh		36.24	54.72
61	Senar	Mazandaran	36.50	51.25
62	Shurjeh	Ghazvin	35.96	48.33

Table 2 (*Continued*)

	Site	Province	N	E
63	Jarandagh		36.11	49.48
64	Abadan	Khuzestan	30.35	48.29
65	Mahshahr		30.54	49.18
66	Shushtar		32.04	48.85
67	Hoseynie		32.21	48.40
68	Soltanye	Zanjan	36.56	48.85

jobs. In solitary areas or areas with a weak grid, wind energy can be used for charging batteries or can be combined with a diesel engine to save fuel whenever wind is available. Moreover, wind turbines can be used for the desalination of water in littoral areas with little fresh water, for instance the Middle East [1].

Some of the drawbacks of wind energy are also mentioned. Wind turbines create a certain amount of noise when they produce electricity. In modern wind turbines, manufacturers have managed to reduce almost all mechanical noise and are now working hard on reducing aerodynamic noise from the rotating blades. Noise is an important rivalry factor, especially in densely inhabited areas. Some people think that wind turbines are unsightly in the vista, but as bigger and bigger machines gradually replace the older smaller machines, the actual number of wind turbines will be reduced while still increasing capacity. If many turbines are to be erected in a region, it is important to have public approval. This can be achieved by allowing those people living close to the turbines to own a part of the project and thus share the income. Furthermore, noise and visual impact will in the future be less important as more wind turbines will be sited offshore.

A wind farm, when installed on agricultural land, has one of the lowest environmental impacts of all energy sources:

1. It occupies less land area per kilowatt-hour of electricity generation of any other energy conversion system, apart from rooftop solar energy.
2. It generates the energy used in its construction in just 3 months of operation, yet its operational lifetime is 20–25 years.
3. Greenhouse gas emissions and air pollution produced by its construction is very low and declining.
4. In substituting for base-load coal power, wind power produces a net decrease in greenhouse gas emissions and air pollution, and a net increase in biodiversity.
5. Modern wind turbines are almost silent and rotate so slowly (in terms of revolutions per minute) that they are rarely a hazard to birds.

Because of the demand for energy in the future, we must explore all aspects of energy production and consumption, including energy efficiency, clean energy, the global carbon cycle, carbon sources, and sinks and biomass, as well as their relationship to climate and natural resource issues. The knowledge of energy has allowed humans to flourish in numbers inconceivable to our ancestors.

All alternative energy technologies are not equal. They have various risks and drawbacks. When evaluating our energy options, we must consider all aspects, including performance against known criteria, basic economics and benefits, efficiency, processing and utilization requirements, infrastructure requirements, subsidies and credits, and waste and the ecosystem, as well as unintended consequences such as impacts on natural resources and the environment.

The advantages of renewable energy are that it is sustainable (nondepletable), ubiquitous (found everywhere across the world in contrast to fossil fuels and minerals), and essentially nonpolluting. The disadvantages of renewable energy are low density and variability, resulting in higher initial cost due to the need for large capture area and storage or backup power.

1.2. World Wind Energy (Report 2009)

It is shown in Fig. 1 that worldwide capacity reached 159,213 MW, out of which 38,312 MW were added in 2009. Wind power showed a growth rate of 31.7%, as the highest rate since 2001. The trend continued that wind capacity doubles every three years. All wind turbines installed by the end of 2009 worldwide are generating 340 TWh per annum. The market for new wind turbines showed a 42.1% increase. Ten years ago, the market for new wind turbines had only a size of 4 GW, only one tenth of the size of 2009. The wind sector in 2009 had a turnover of 70 billion US$ in the year 2009, compared with 56 billion US$ in the previous year. The wind sector employed 550,000 persons worldwide. In the year 2012, the wind industry is expected for the first time to offer 1 million jobs. China continued its development in wind industry and added 13,800 MW within one year as the biggest market for new turbines. The USA maintained its number one position in terms of total installed capacity, and China became number two in total capacity, only slightly ahead of Germany, both of them with around 26,000 Megawatts of wind capacity installed. Asia accounted for the largest share of new installations (40.4%), followed by North America (28.4%) and Europe fell back to the third place (27.3%). Latin America showed encouraging growth and more than doubled its installations, mainly due to Brazil and Mexico. A total wind capacity of 200,000 Megawatt will be exceeded within the year 2010. Based on accelerated development and further improved policies, WWEA increases its predictions and sees a global capacity of 1,900,000 Megawatt as possible by the year 2020 [2].

In the year 2009, altogether 82 countries used wind energy on a commercial basis, out of which 49 countries increased their installed capacity. China and the USA established themselves as the by far largest markets for new wind capacity, together accounting for 61.9% of the additional capacity, a share which was substantially bigger than in the previous year (53.7%). As shown in Fig. 2, top 10 countries in usage of wind energy are: USA, China, Germany, Spain, India, Italy, France, United Kingdom, Portugal and Denmark [2].

Fig. 3 shows the country share of new capacity in the year 2009. The USA and China together represented 61.9% of the new capacity installed. The top five countries (USA, China, Germany, Spain and India) represented 76.7% of the worldwide wind capacity [2].

Asia became the world's wind locomotive in the year 2009, mainly due to the two large markets: China and India. The total installed wind capacity in Asia reached 40 Giga watt (25.1% of the global capacity). The continent had the second highest growth rate of all world regions (63.3%, after 54.1% in 2008) and added 15.5 Giga watt in 2009 [2].

1.3. Wind power in Iran

It is known that the supplies of fossil fuels are limited and their utilization as energy sources causes environmental degradation due to incomplete combustion when used as energy source.

Table 3
Annual mean wind speed at 3 heights and annual Weibull distribution constants (k, c) for sites.

Height Site	10 m	30 m	40 m	10 m		30 m		40 m	
	$U_{average}$			k	c	k	c	k	c
Ardabil									
Meshkin Shahr	4.005108	4.190304	4.310926	1.177	4.645	1.097	4.685	1.192	4.194
Namin	4.198607	4.733706	4.949611	1.106	4.744	1.099	5.053	1.089	5.164
Province: East Azarbaijan									
Oscoo	4.822736	5.184331	5.231362	1.64	5.259	1.558	5.524	1.542	5.538
Ahar	7.463883	7.496425	7.70855	1.57	7.34	1.539	7.067	1.543	7.169
Bonab	3.163873	3.837891	4.051558	1.365	3.891	1.391	4.479	1.388	4.724
Mayan	4.183028	5.162026	5.4521	1.648	4.82	1.645	5.979	1.631	6.243
Province: West Azarbaijan									
Chaldoran	3.595046	3.889553	3.973548	1.191	4.229	1.215	4.459	1.218	4.45
Province: Isfahan									
Brojen	3.171752	3.57992	3.749224	1.167	4.134	1.13	4.319	1.113	4.485
Moghar	3.463003	4.159527	4.406123	1.599	4.056	1.584	4.668	1.577	4.822
Morchekhort	3.740963	4.422291	4.688671	1.695	4.233	1.721	4.881	1.709	5.109
Varzaneh	4.148854	4.940189	4.940189	1.559	4.604	1.465	5.042	1.447	5.182
Province: Tehran									
Eshtehard	4.806924	5.550729	5.87315	1.643	5.039	1.732	5.7	1.726	5.984
Kahrizak	3.019389	4.043084	4.201562	1.4	3.96	1.511	4.812	1.578	5.2
Latman	4.08733	4.3592	4.531	1.785	4.597	1.635	4.875	1.518	5.031
Province: Markazi									
Khomeyn	3.330732	3.815686	3.933919	1.417	4.061	1.321	4.537	1.319	4.649
Province: Hamedan									
Nahavand	2.504	2.8758	3.06878	1.178	3.597	1.2	3.742	1.026	3.817
Rasul Abad	3.949298	4.436162	4.58734	1.305	4.781	1.238	5.144	1.206	5.308
Kabodarahang	3.955	4.404	4.5805	1.484	4.433	1.417	4.847	1.399	4.952
Province: Bushehr									
Delvar	3.335835	4.0185	4.253651	1.565	3.715	1.712	4.509	1.743	4.778
Bardkhoon	4.5	5.36	5.83	1.737	5.058	1.85	6.037	1.848	6.568
Province: North Khorasan									
Esfarayen	3.556342	4.220059	4.372213	1.555	4.156	1.487	4.851	1.461	4.884
Bojnurd	4.968817	5.36313	5.564495	1.553	6.095	1.596	6.393	1.624	6.512
Province: RazaviKhorasan									
Davarzan	3.260138	3.970418	4.193514	1.445	3.715	1.399	4.259	1.38	4.371
Sarakhs	3.788401	4.598339	4.797545	1.549	4.513	1.63	5.057	1.637	5.219
Ghadamgah	4.201008	5.052572	5.247578	1.331	4.576	1.291	5.183	1.29	5.328
Khaf	9.208551418	10.43955	10.81669	1.618	10.34	1.611	11.81	1.643	12.48
Jangal	3.76819	4.525803	4.786545	1.95	4.41	1.945	5.352	1.907	5.61
Rudab	4.959593	5.987257	6.196662	1.696	5.051	1.612	6.094	1.587	6.267
Afriz	4.472699	5.243108	5.42039	1.378	5.517	1.351	5.99	1.366	6.125
Province: South Khorasan									
Fadashk	5.27	6.2	6.33	1.933797	5.946789	2.021352	7.006467	2.016503	7.147757
Nehbandan	5.05	5.68	5.86	1.342	5.505	1.329	6.189	1.323	6.374
Province: Kermanshah									
Mahi Dasht	2.809956	3.348311	3.598008	1.349	3.653	1.335	4.423	1.34	4.229
Province: Kordestan									
Divandare	3.602293	4.478171	4.228319	1.288	4.372	1.443	5.118	1.4	4.886
Ghorve	4.283024	4.71745	4.873128	1.395	4.868	1.249	5.198	1.24	5.286
Province: Khuzestan									
Shushtar	2.152538956	3.044832	3.401105	1.364	3.181	1.437	3.917	1.438	4.168
Hoseynie	4.01356036	5.086264	4.989186	1.452	4.576	1.486	5.885	1.542	5.767
Abadan	4.031396888	4.922331	5.730037	1.841	4.579	2.142	5.667	2.345	6.624
Mahshahr	4.363516636	3.198465	6.210877	2.003	4.863	2.32	5.911	2.36	7.04
Province: Fars									
Javim	1.98803	2.359494	2.518007	1.118	3.365	1.126	3.531	1.144	3.602
Marvdasht	2.849814	3.239656	3.373743	1.48	3.73	1.486	4.145	1.526	4.182
Abade	4.031397	4.922331	5.730037	1.841	4.579	2.142	5.667	2.345	6.624
Eghlid	4.307892	4.787328	4.970294	1.305	4.718	1.241	5.053	1.266	5.172
Province: Kerman									
Rafsanjan	4.418475	5.130751	5.384988	2.1	5.317	2.087	5.804	2.047	6.048
Arzooye	3.236178	3.541807	3.615695	1.538	4.034	1.573	4.321	1.598	4.35
Shahre Babak	3.584309	4.169709	4.344508	1.629	4.228	1.594	4.692	1.603	4.878
Province: Golestan									
Agh Ghala	3.001277	3.730671	3.979982	1.58	3.689	1.732	4.419	1.725	4.711
Marave Tappe	3.541591	3.914553	4.056442	1.489	4.386	1.532	4.669	1.541	4.8

Table 3 (*Continued*)

Height Site	10 m	30 m	40 m	10 m		30 m		40 m	
	$U_{average}$			k	c	k	c	k	c
Province: Hormozgan									
Jask	3.257952	3.966645	4.243292	1.595	4.023	1.823	4.664	1.839	4.938
Kish	4.376437	4.866661	5.164958	1.722	4.921	1.828	5.42	1.793	5.652
Province: Yazd									
Behabad	4.117	4.404	4.5764	1.805	4.807	1.572	5.14	1.491	5.242
Halvan	3.9177	4.5144	4.6898	1.643	4.43	1.573	5.021	1.529	5.24
Ardakan	3.5078	4.1315	4.358	1.566	4.116	1.482	4.649	1.482	4.805
Korit	2.9116	3.4172	3.6173	1.406	3.678	1.372	4.073	1.366	4.217
Abarkuh	3.3919	3.99	4.275	1.656	4.007	1.556	4.591	1.58	4.745
Province: Sistan and Baluchistan									
Delgan	3.0567	4.144545	4.487886	1.406	3.517	1.577	4.677	1.561	4.908
Dehak	3.687166	4.278628	4.508631	1.289	4.411	1.374	4.815	1.416	5.032
Lutak	4.817591659	6.49715	7.004191	1.41	5.088	1.599	6.615	1.619	7.178
Nosrat Abad	4.2017	4.833638	5.0135	1.641	4.354	1.817	5.672	1.809	5.776
Chabahar	4.886516465	5.298474	5.51016	2.241	5.595	2.392	5.947	2.402	6.116
Khash	3.801842	4.325152	4.578226	1.308	4.411	1.322	4.966	1.355	5.245
Province: Gilan									
Langrood	2.858675	3.611259	3.790124	1.339	3.765	1.698	4.227	1.775	4.418
Province: Semnan									
Kahak	3.613	4.563	4.875	1.783	4.282	1.718	5.499	1.694	5.802
Haddadeh	4.674	5.466	5.857	1.524	5.189	1.575	6.0897	1.567	6.5224
Moalleman	4.9321	5.818	6.1661	1.615	5.582	1.655	6.616	1.654	6.914
Province: Mazandaran									
Senar	2.366499	2.517705	2.589911	1.204	3.5	1.052	3.909	1.074	3.826
Province: Ghazvin									
Shurje	5.9531	6.814084	7.024321	1.536	6.294	1.466	7.029	1.455	7.192
Jarandagh	5.9531	6.814084	7.024321	1.536	6.294	1.466	7.029	1.455	7.192
Province: Zanjan									
Soltanie	3.485	4.373	4.6032	1.082	4.538	1.127	4.954	1.142	5.23

In addition, as the world population increases, the demand for energy sources increases, too; therefore, the issue of a gradual replacement of fossil fuels with renewable energy sources is of major consideration for most countries. Studies and evaluations regarding the wind potential estimation in Iran show that in 26 sections of the country (including more than 45 suitable sites) the nominal capacity of the sites, considering a general efficiency of 33%, is approximately 6500 Megawatt; however, it is noteworthy that the nominal capacity of all power plants of the country is already 3400 [3]. The feasibility of manufacturing wind turbines is investigated in this article. Utilization of renewable energy sources in Iran began a decade ago and it is still in its initial stages of development.

The geographical condition of Iran is such that its low air pressures produce strong air flows over it in general during the summer and winter in comparison with high pressures in the north and northwestern areas. There is an air pressure difference between the atmosphere over Iran, Central Asia as well as the Atlantic Ocean during the winter that causes cold winds from the north and humid air flows from the Atlantic and Mediterranean from the west.

Iran's first experience in installing and using modern wind turbines dates back to 1994. Two sets of 500 kW NORD-TANK wind turbines were installed in Manjil and Roodbar. They produced more than 1.8 million kWh per year. These two sites are in the north of Iran, 250 km from Tehran, the capital of Iran. The average wind speed is 15 m/s for 3700 h per year in Roodbar, and 13 m/s for 3400 h per year in Manjil. After this successful experience, in 1996 the contract for 27 wind turbines was signed and they were installed by 1999 in Manjil, Roodbar and Harzevil. Harzevil is the third wind farm site near to Manjil. Manjil is about 800 meters above sea level and Harzevil is about 500 meters higher. There are 21 installed wind turbines in Manjil, 1×500 kW, 5×550 kW and 15×300 kW[4] (Manjil wind farm is shown in Fig. 4).

In 2006, Iran generated 47 Megawatts of electricity from wind power (ranked 30th in the world). This was a 47% increase over 32 Megawatts in 2005. Total wind generation in 2004 was 25 Megawatts out of 33,000 Megawatts of total electrical generation capacity for the country.

The next large wind farm was commissioned in Dizbad at the Binaloud mountain which is located in the northeastern part of Iran. It is a wind tunnel of 50 kilometers in length and 5 kilometers in width through which wind steadily flows at a mild velocity of 8.9 m/s. This wind farm includes forty three 660 kW wind turbines with the total capacity of 28.4 MW. Up to now, twenty wind turbines have been installed and delivered electricity to the grid. The 660 kW wind turbines (V47—660 kW) are manufactured by a domestic company under the license of a Danish company. According to the available technology, economic studies and their searches on the Iran's wind potential, it is estimated that the power generation potential in Iran by the application of wind turbines is around 15,000 MW [5].

In 2008, Iran's wind power plants in Manjil (in Guilan province) and Binaloud (in Khorasan Razavi province) produce 82 Megawatts of electricity per year. By 2009, Iran had wind power installed capacity of 91 MW [6].

Assessment of wind energy potential in Iran has been done for some areas such as Manjil in Guilan province [7], Yazd [8], Tehran [9] and Semnan [10] provinces. There are also studies on the feasibility of offshore wind turbine installation in Iran and its comparison with the world [11], the future of renewable energies in Iran [12] and renewable energy issues in Middle East compared with Iran [13]. Recent discussions can be seen in Fig. 5.

1.4. About Iran

Iran and ancient Persia have a long, creative and glorious history. Today, Iran has a population of about 75 million persons. Principal ethnic groups are Persian 51%, Azeri 24%, Gilaki and Mazandarani 8%, Kurd 7% and Arab 3%. Iran is a Muslim country, with 89% Shi'a and 10% Sunni Muslims. The remaining 1% belongs to Jewish and Zoroastrian faiths. Major languages of Iran are Persian (Fars) and Persian dialects 58%, Turkic and Turkic dialects 26%, Kurdish 9%, Luri 2%, Baluchi 1%, Arabic 1%, and Turkish 1% [14].

As shown in Fig. 6, Iran is subdivided into thirty provinces. Each is governed from a local center, and the largest local city, usually

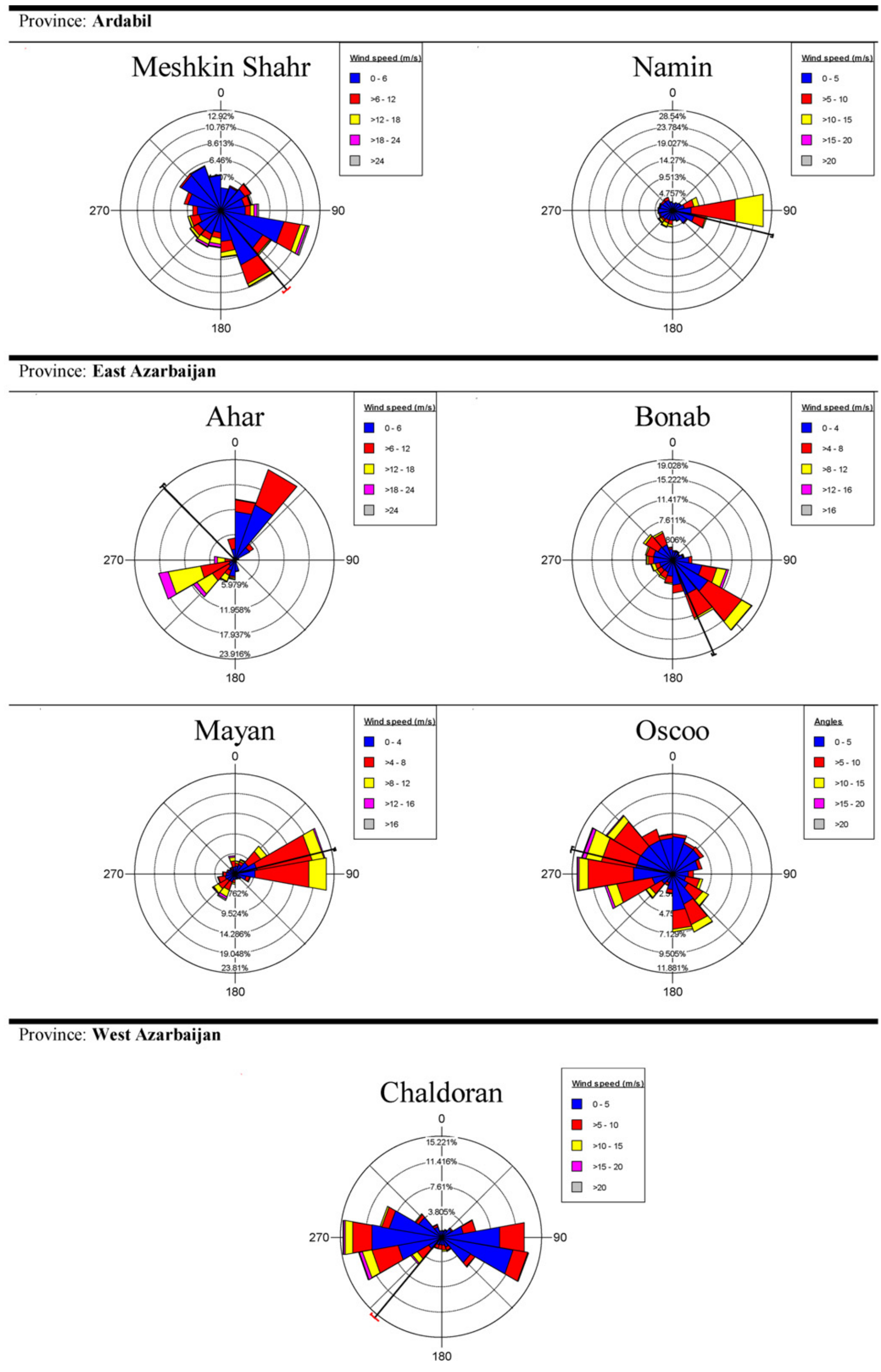


Fig. 7. Wind rose diagrams at 30 m.

is called the capital of that province. The provincial authority is headed by a Governor-General, who is appointed by the minister of the interior upon approval of the cabinet (The guide of Iran map can be seen in Table 1).

Iran is situated in Southwest Asia, the Middle East. It is bordered on the eastern side of Iraq and Turkey, western side of Afghanistan and Pakistan and southern side of Azerbaijan, Armenia and Turkmenistan. The largest lake of the world, Caspian Sea, is in Northern Iran and The Persian Gulf as well as Oman Sea is southern Iran.

Iran extends over an area of 1,648,000 square kilometers, making it the second largest country in the Middle East after Saudi Arabia. The Caspian coastline, in Northern Iran, is extended as long as 650 kilometers. The southern coastline of Iran, including the Persian Gulf and Oman Sea, is approximately 1770 kilometers [15].

The growth of the population during the recent decades has resulted in growing populations in some cities of Iran. Tehran, the capital of Iran, is inhabited by approximately 14 million people. It also hosts an additional 4 million who commutes to the

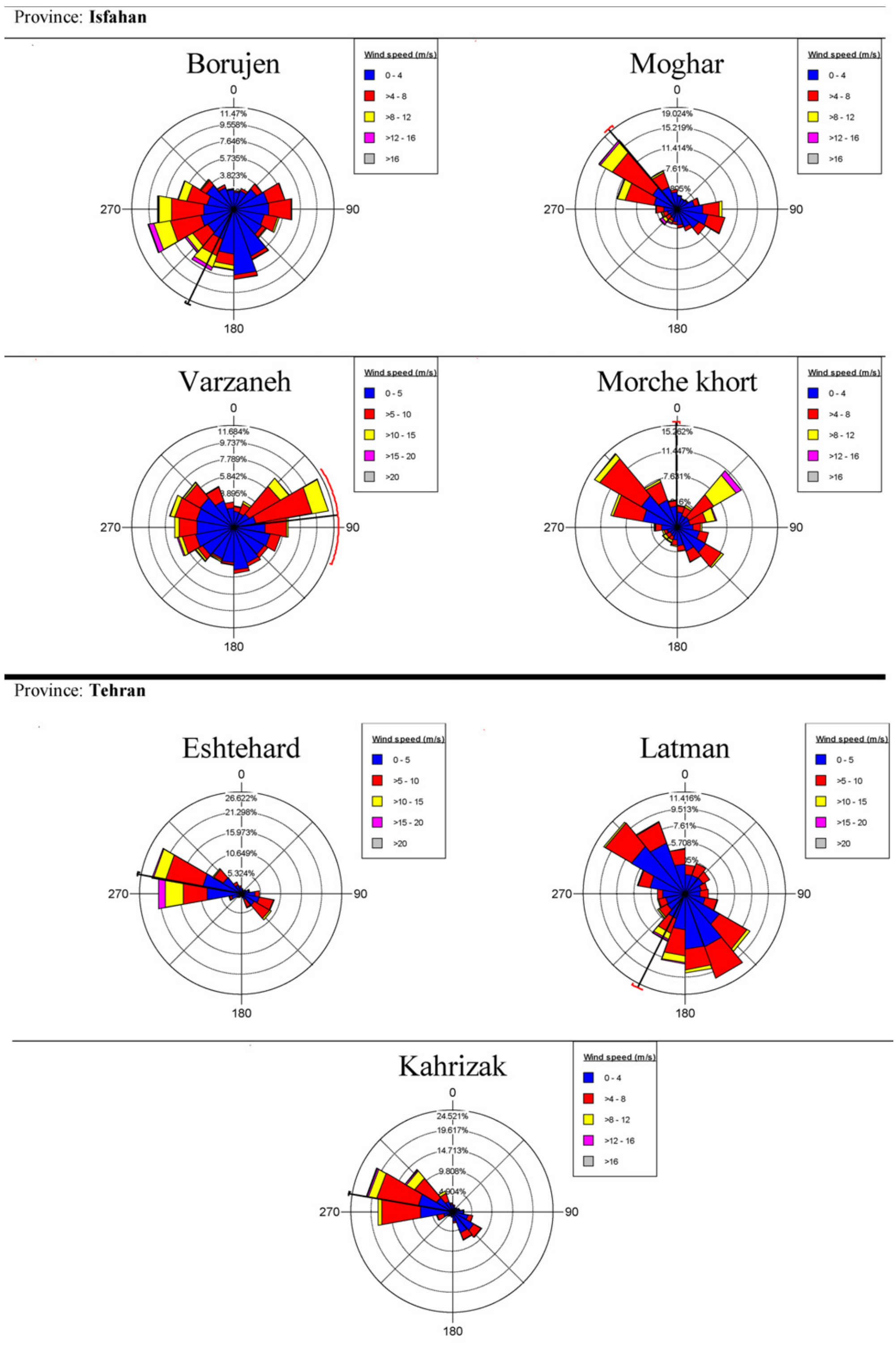


Fig. 7. (*Continued*)

city for work every day. However, there are some other cities of Iran that are growing into industrial centers of Iran. They consist of Arak, Ahvaz, Isfahan, Kerman, Shiraz, Tabriz, Semnan, and Mashhad.

There are different geographical areas in Iran with the quality of terrain particular to those areas. Around 1/3 of Iran's entire territory is arable and only 10.4% is under cultivation. Almost 6% of the total land is used for pasture. Forested areas, which are mainly on the northern coastal areas of Iran, account for 4.5% of the total territory.

As a whole, looking at the geography of the world, you will soon find out that Iran is one of the most mountainous countries of the world.

In addition to other local mountain ranges, there are two major mountain ranges in Iran:

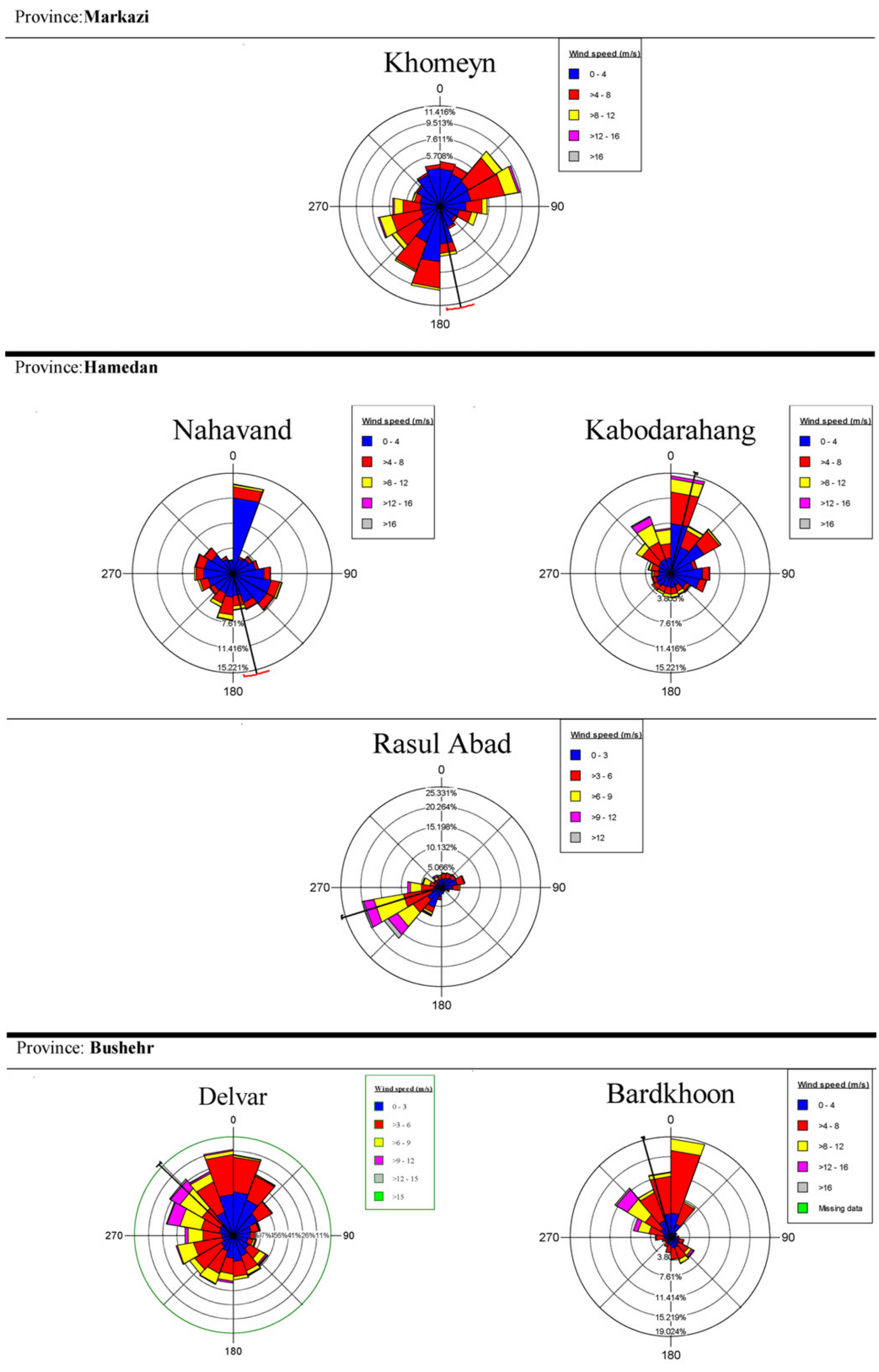


Fig. 7. (*Continued*)

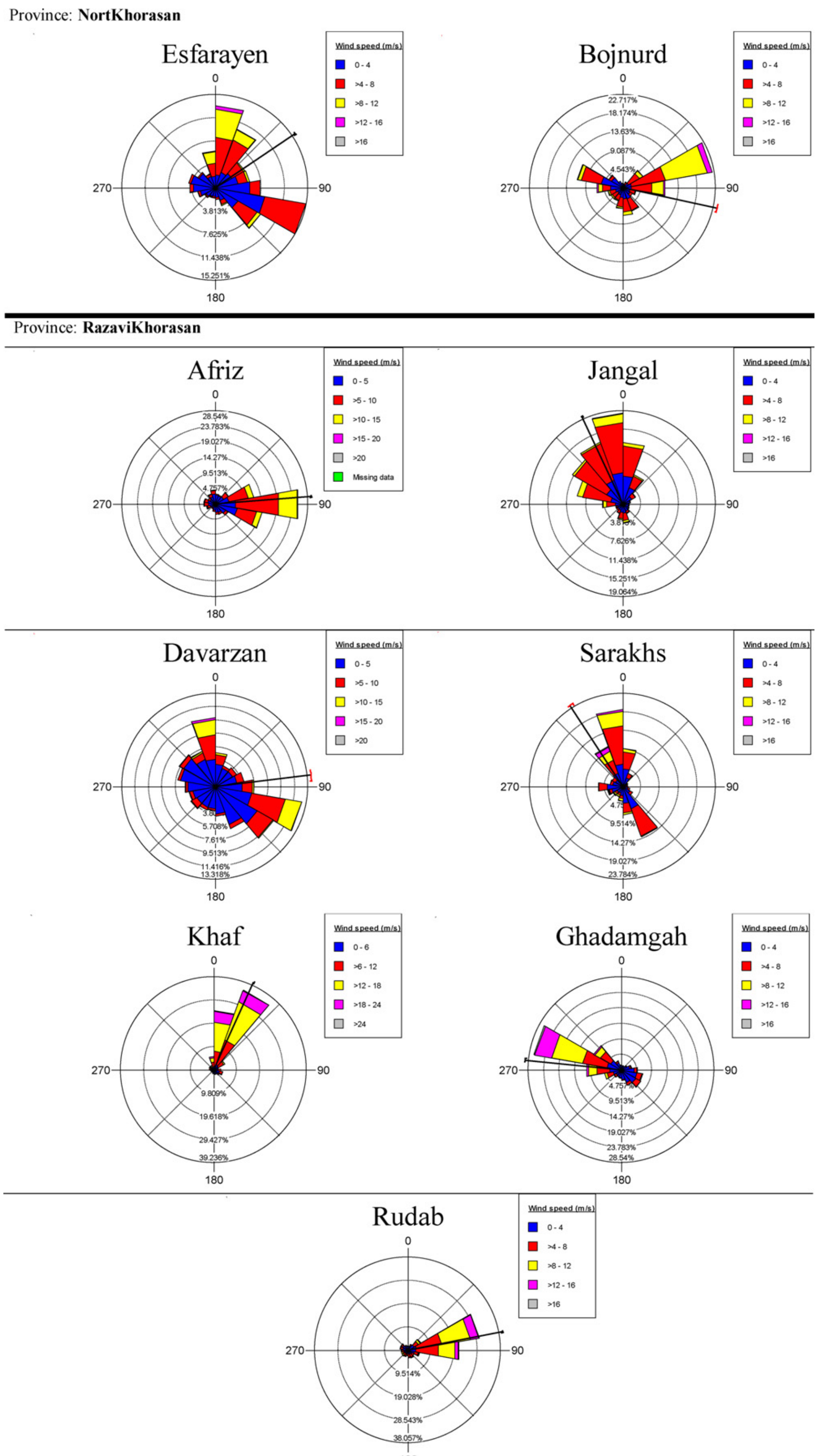


Fig. 7. (*Continued*)

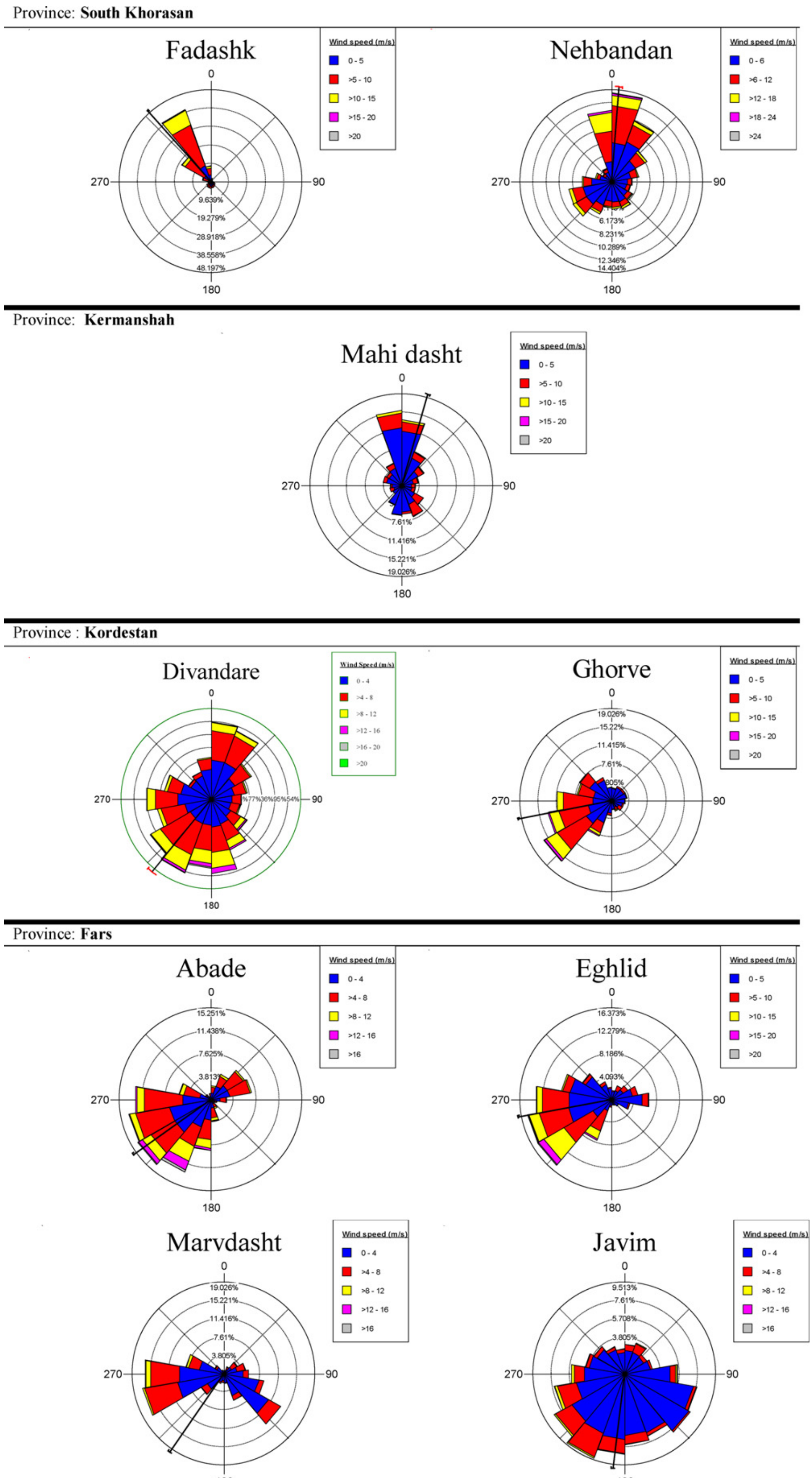


Fig. 7. (*Continued*)

1. The Alborz Mountain Range: It extends from the Northwest to Northeast of Iran with the highest peak (Damavand, 5671 meters above sea level) near Tehran.
2. The Zagros Mountain Range: It extends from the Northwest to the Southwest and Southeast of Iran with several peaks higher than 4000 meters above sea level.

The deserts of Iran are mainly situated on the Eastern half of Iran. The two major deserts in Iran are called:

1. Dasht-e-Kavir, which is located in central Iran toward East.
2. Kavir-e-Lut, which is in Southeastern Iran.

There are different climatic districts in Iran. Some of them are so varied that they seem to compose a list of all climates you may find at different parts of the world.

- The Caspian coastal plain remains humid all year due to the low altitude of nearly close to the sea level.

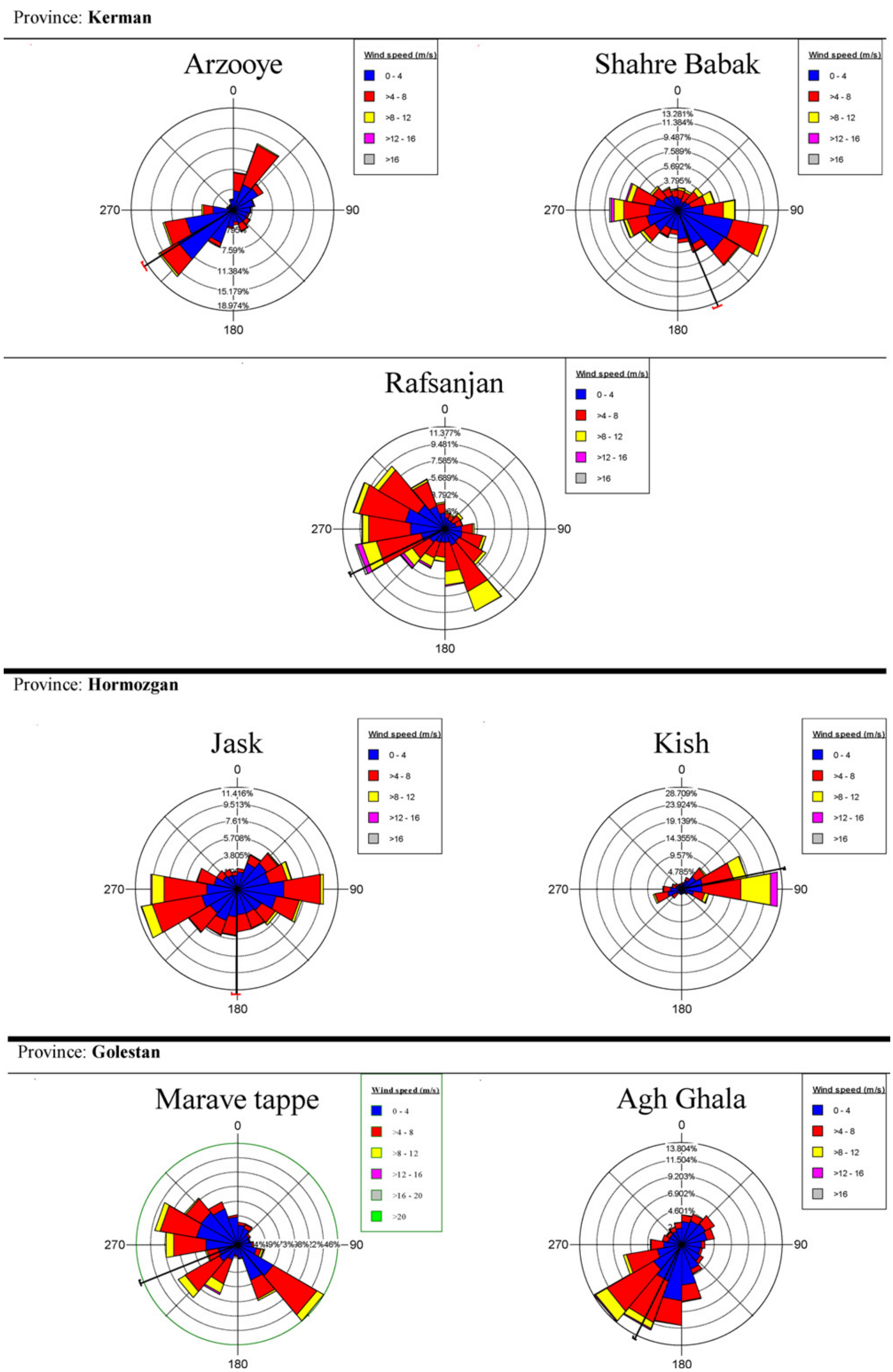
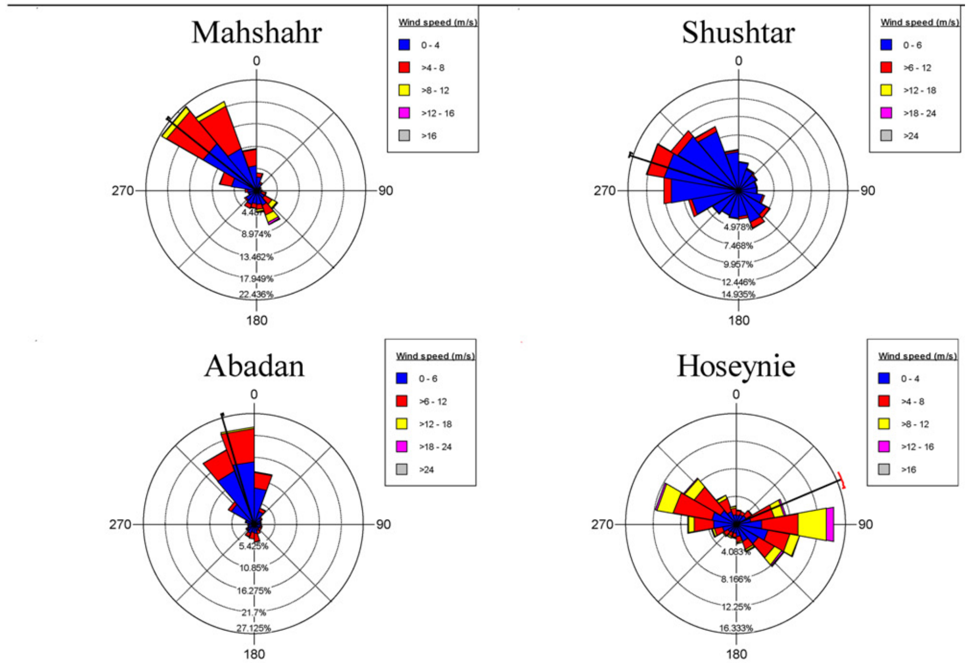


Fig. 7. (*Continued*)

Province: **Khuzestan**



Province: **Yazd**

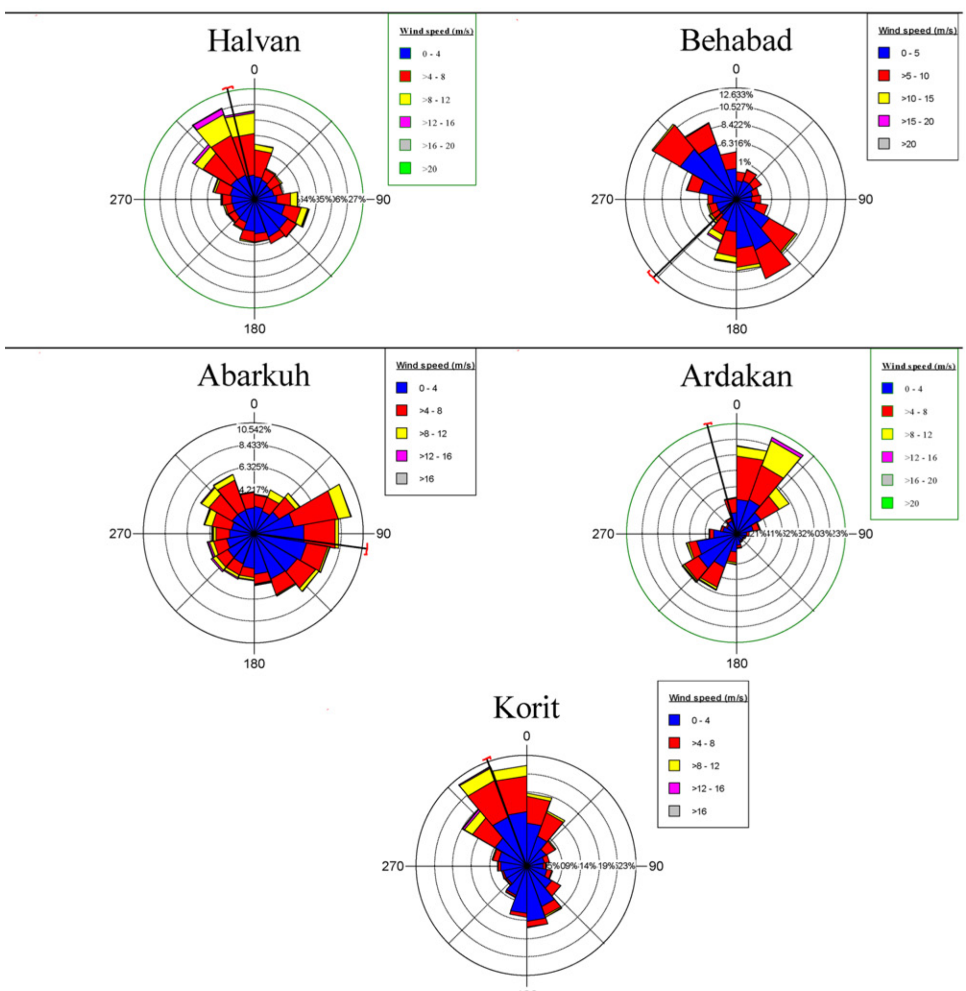


Fig. 7. (*Continued*)

- The high altitude of inhabited areas in western Iran creates a cold winter that is usually below the freezing point.
- The central and Eastern Iran goes through seasonally climatic variations. In general, these areas are arid and semi-arid during most parts of the year.
- The Southern coastal plains of Iran have mild winters, and very hot and extremely humid summer days. The temperature could exceed 48 °C during July in the interior part of Southern Iran.

In this paper, we have studied the feasibility of wind energy in different provinces of Iran and compared it with the other acceptable sources by analyzing the speed of the winds and its potentials. Also the location of meteorological sites is shown in Table 2.

2. Analysis of wind data

In this study, data was collected during a period of one year, from 1/1/2007 to 12/31/2007 in the time interval of 10 min. The data logger used has three sensors of velocity at 10 m, 30 m and 40 m heights and also two sensors of direction at 30 m and 37.5 m [3].

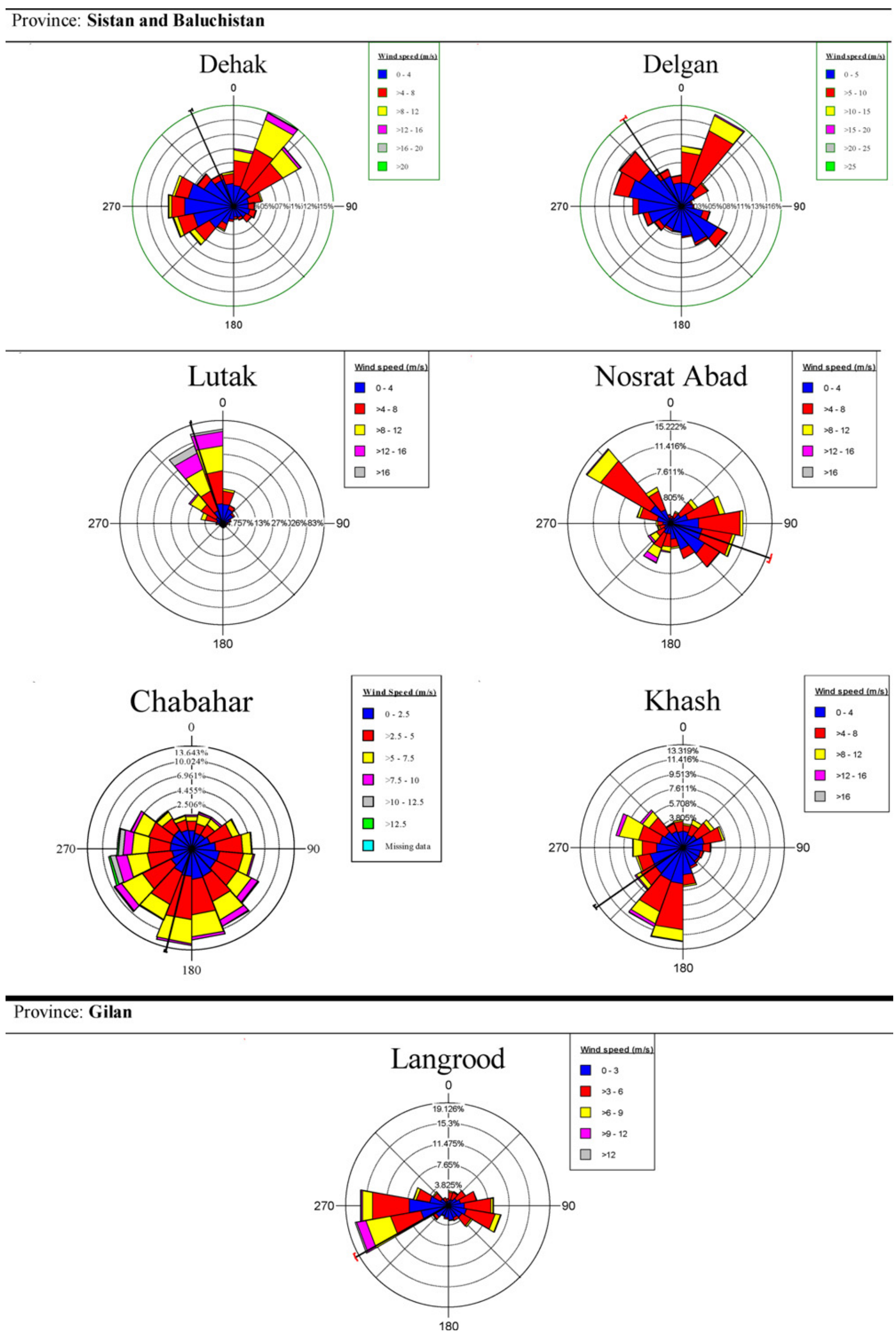
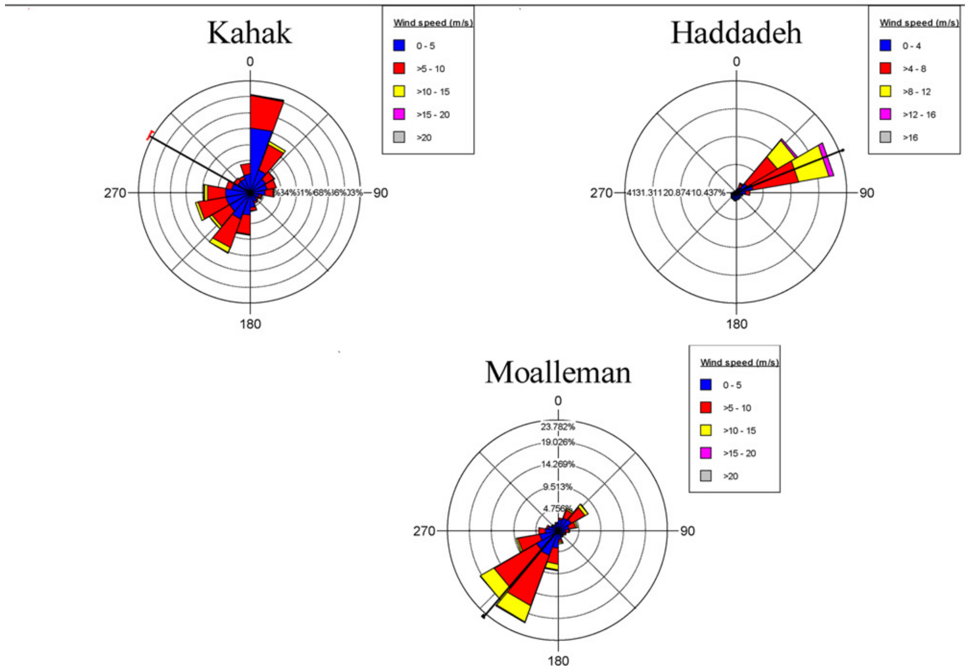
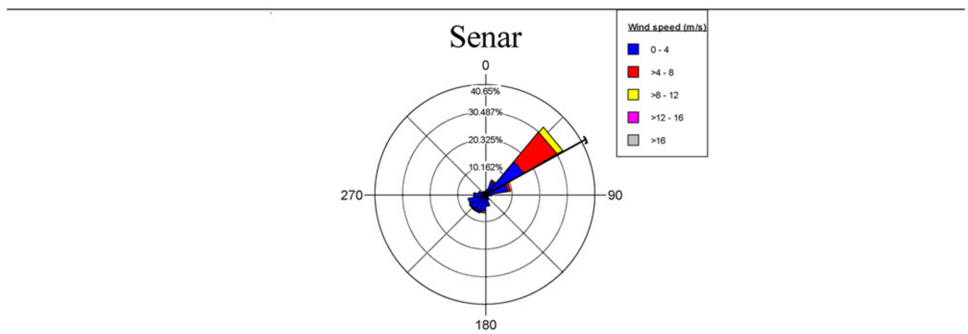


Fig. 7. (*Continued*)

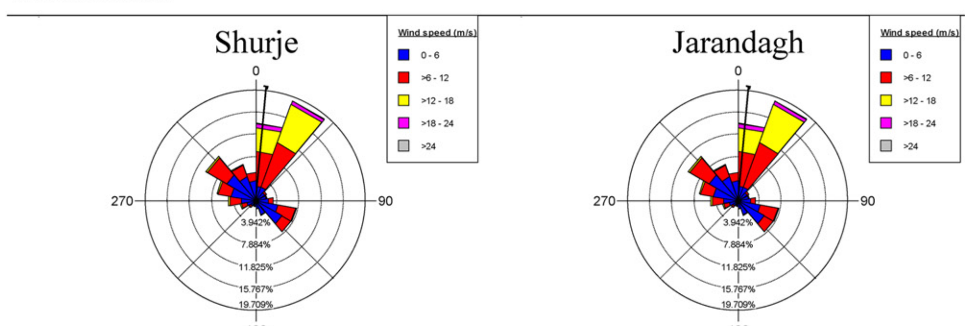
Province: **Semnan**



Province: **Mazandaran**



Province: **Ghazvin**



Province: **Zanjan**

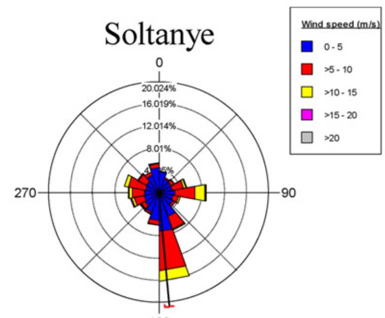


Fig. 7. (*Continued*).

2.1. Average wind speed

As shown in Table 3, in the first phase of the study, the one-year average wind speed at 3 heights was determined for different areas.

2.2. Wind speed distribution

Statistical analysis can be used to determine the wind energy potential of a given site and estimate the wind energy output at this site. To describe the statistical distribution of wind speed, various probability functions can be suitable for wind regimes. According to Gumbel [17], Weibull distribution is the best one, with an acceptable accuracy level. This function has the advantage of making it possible to quickly determine the average of annual production of a given wind turbine. The Weibull probability density function is given by [18]:

$$p(U) = \left(\frac{k}{c}\right)\left(\frac{U}{c}\right)^{k-1} \exp\left[-\left(\frac{U}{c}\right)^{k}\right] a \quad (1)$$

Determination of the Weibull probability density function requires knowledge of two parameters: k, shape factor and c, scale factor. Analytical and empirical methods are used to find k and c, such as Justus formulas demonstrated in the following form [18]:

$$\sigma_u = \sqrt{\frac{\sum_{i=1}^{N}(U_i - \overline{U})^2}{N-1}} \quad (2)$$

$$k = \left(\frac{\sigma_U}{\overline{U}}\right)^{-1.086}, \quad \frac{c}{\overline{U}} = \frac{k^{2.6674}}{0.184 + 0.816k^{2.73855}} \quad (3)$$

where σ_{u} and $\overline{U}$ represent the Standard deviation and mean wind speed, respectively. Standard deviation is also defined through the value of k [18]:

$$\sigma_U = \overline{U}\sqrt{\left(\frac{\Gamma(1+2/k)}{\Gamma^2(1+1/k)} - 1\right)} \quad (4)$$

Also Table 3 shows annual Weibull distribution constants (k and c) for three heights of Iran provinces. It is also noticed that the Weibull distribution gives a good fit to experimental data.

The energy pattern factor, K_e, whose application is in turbine aerodynamic design, can be defined as the total amount of power available in the wind divided by the power calculated from cubing the average wind speed is given by [18]:

$$K_e = \frac{1}{N\overline{U}^3}\sum_{i=1}^{N} U_i^{\,3} = \frac{\overline{U^3}}{(\overline{U})^3} = \frac{\Gamma(1+3/K)}{\Gamma^3(1+1/K)} \quad (5)$$

where N is the amount of data in a year. Tables 4 and 5 show the wind characteristics.

In the study of wind energy feasibility, to determine maximum energy throughout the year, the nominal wind speed is used as a speed that produces maximum energy all over the year. This speed is one of the significant characters in turbine designing and is given by [18]:

$$U_{me} = c\left(\frac{k+2}{k}\right)^{1/k} \quad (6)$$

It can also find the most probable wind speed for the area from [18]:

$$U_{mp} = c\left(1 - \frac{1}{k}\right)^{1/k} \quad (7)$$

In Table 4, the above-mentioned cases were also represented for three heights.

2.3. Surface roughness

Although there are a number of ways to arrive at a prediction of a logarithmic wind profile (e.g., mixing length theory, eddy viscosity theory, and similarity theory), a mixing length type analysis given by Wortman (1982) is by the log law [18]:

$$\frac{U(z)}{U(z_r)} = \frac{\ln(z/z_0)}{\ln(z_r/z_0)} \quad (8)$$

where $U(z)$ is the wind speed at height z, $U(z_r)$ is the reference wind speed at reference height z_r, and z_0 is the surface roughness length, which characterizes the roughness of the terrain.

With respect to mean wind speeds at 10 m, 30 m and 40 m, and the curve fitting logarithmic profile (log law), the equivalent surface roughness length of terrain can be found. Table 5 shows the surface roughness length.

2.4. Wind direction

The wind direction is of paramount importance for the possibility assessment of using wind energy, and plays a significance role in the optimal positioning of a wind farm in a given area.

Above we have estimated the mean wind speed without evoking the influence of the direction in the distribution of this parameter. In this section the frequency with which the wind direction falls within each direction sector is evaluated, so we present the data collected in the form of wind rose.

Table 5 shows the Annual mean wind direction for two heights. Limitation of wind direction has a significant preference for wind powerhouse.

One way to define the probability density function is that the probability of a wind speed occurring between U_a and U_b is given by [18]:

$$p(U_a \le U \le U_b) = \int_{U_a}^{U_b} p(U)\,\mathrm{d}U \quad (9)$$

Also, the total area under the probability distribution curve is given by:

$$\int_{0}^{\infty} p(U)\,\mathrm{d}U = 1 \quad (10)$$

For example, the probability of a wind speed happen upper than 5 m/s is shown in Table 6.

2.5. Power density

The best way to evaluate the wind resource available at a potential site is calculating the wind power density. It indicates how much energy is available in the site for converting to electricity by a wind turbine. The wind power per unit area, P/A or wind power density is [18]:

$$\frac{\bar{P}}{A} = \frac{1}{2}\rho\int_{c}^{\infty} U^3 p(U)\,\mathrm{d}U = \frac{1}{2}\rho c^3\,\Gamma\left(\frac{1+3}{k}\right) \approx \frac{1}{2}\rho\overline{U^3} \quad (11)$$

For standard conditions (sea level, ISOC), the density of air is 1.225 kg/m^3. There are mainly two ways to estimate the power density in the site. The first is based on the measured data and the second on the probability distribution function. However, the first method is more precise because of its uses. The annual power density is determined using Eq. (11). Table 6 also compared the results

Table 4
U_{me}, U_{mp}, and K_e of sites.

Parameter	U_{me}			U_{mp}			K_e		
Height Site	10 m	30 m	40 m	10 m	30 m	40 m	10 m	30 m	40 m
Province: Ardabil									
Meshkin Shahr	10.7988	12.06671	9.54539	0.92879	0.513361	0.906527	4.151202	4.82224397	4.046451
Namin	12.06734	12.97825	13.51948	0.569252	0.565399	0.517889	4.735798	4.80275895	4.901804
Province: East Azarbaijan									
Oscoo	8.551372	9.385237	9.666241	2.962906	2.857802	2.811091	2.399957	2.57350328	2.611463
Ahar	12.38617	12.14004	12.34692	3.849688	3.574097	3.643408	2.545979	2.61874661	2.609047
Bonab	7.535856	8.499603	8.941205	1.480466	1.798685	1.885789	3.154982	3.05778956	3.068637
Mayan	7.806402	9.697911	10.22683	2.735664	3.384165	3.487605	2.384704	2.3903919	2.417446
Province: West Azarbaijan									
Chaldoran	9.674136	9.932539	9.812396	0.909564	1.071998	1.083685	4.053259	3.89638046	3.877687
Province: Isfahan									
Brojen	9.725276	10.64011	11.63043	0.781349	0.637221	0.53299	4.224299	4.51997641	4.745248
Moghar	6.736651	7.816324	8.136967	2.194915	2.486315	2.548807	2.482605	2.51484525	2.530283
Morchekhort	6.703794	7.639988	8.021993	2.501616	2.944142	3.053214	2.300312	2.25716071	2.276782
Varzane	7.817696	9.074051	9.651938	2.38461	2.303608	2.301086	2.571179	2.81690386	2.871118
Province: Tehran									
Eshtehard	8.181372	8.879029	9.224679	2.846867	3.466716	3.623152	2.394205	2.23960149	2.249129
Kahrizak	7.463556	8.407356	8.45796	1.61836	2.348092	2.751634	3.025795	2.68939342	2.528062
Latman	7.004016	7.946921	9.18432	2.901377	2.733726	2.477712	2.16033	2.40962934	2.671267
Province: Markazi									
Khomeyn	7.558068	9.116892	9.56707	1.712902	1.554778	1.584874	2.967524	3.33740485	3.346288
Province: Hamedan									
Nahavand	8.352608	8.473791	11.4891	0.723152	0.840707	0.106169	4.144039	3.99285845	5.632809
Rasul Abad	9.744529	11.18366	12.24529	1.56948	1.35779	1.226157	3.410029	3.75788899	3.953654
Kabodarahang	7.878762	9.02092	9.50662	2.083569	2.044432	2.019889	2.762398	2.96752384	3.02931
Province: Bushehr									
Delvar	6.286692	7.086027	7.203402	1.937461	2.700969	2.929486	2.557351	2.2718305	2.222438
Bardkhoon	7.861933	8.971587	9.614369	3.087629	3.965081	4.308906	2.231752	2.07381733	2.076321
Province: North Khorasan									
Esfarayen	7.073167	8.604967	8.976518	2.142567	2.289907	2.217658	2.580509	2.75403503	2.828729
Bojnurd	10.38513	10.63528	10.5458	3.134818	3.4488	3.613477	2.585208	2.48896326	2.431296
Province: RazaviKhorasan									
Davarzan	6.777677	8.033143	8.481774	1.644274	1.737219	1.716779	2.877304	3.02931011	3.098023
Sarakhs	7.707412	8.264518	8.372898	2.310181	2.822361	2.932139	2.594674	2.41941114	2.405747
Ghadamgah	9.116062	10.69984	11.11559	1.608529	1.634533	1.67529	3.293798	3.47662537	3.481496
Khaf	17.00285	19.4911	20.17791	5.704047	6.469755	7.050783	2.443344	2.45760936	2.394205
Jangal	6.333593	7.698786	8.218591	3.049854	3.692665	3.799456	1.95972	1.96494885	2.006248
Rudab	7.995586	10.05221	10.67607	2.987456	3.341765	3.348779	2.298608	2.45555738	2.508306
Afriz	10.57533	11.73402	11.88394	2.157951	2.2088	2.335541	3.105475	3.21044576	3.151107
Province: South Khorasan									
Fadashk	8.58543	9.846602	9.956089	4.081234	4.998407	5.089112	1.976834	1.88983381	1.894318
Nehbandan	10.86497	12.35058	12.84117	1.987642	2.164666	2.195619	3.247336	3.30241352	3.328577
Province: Kermanshah									
Mahi Dasht	7.167825	8.781234	8.377435	1.340832	1.570189	1.51964	3.218558	3.27672399	3.255669
Province: Kordestan									
Divandare	9.050787	9.350317	8.99111	1.366518	2.257803	1.996795	3.491284	2.883523	3.025795
Ghorve	9.209657	11.17512	11.90923	1.970314	1.429214	1.40591	3.043469	3.69539499	3.746353
Province: Khuzestan									
Abadan	6.827444	7.710023	8.17536	2.991909	4.225038	5.225997	2.08516	1.78897806	1.656219
Shushtar	6.165726	7.186287	7.526648	1.207683	1.710777	1.823467	3.158869	2.90238349	2.899219
Mahshahr	6.871181	7.72749	8.806579	3.443017	4.635478	5.573697	1.907002	1.67054723	1.647857
Hoseynie	8.308276	10.44587	9.72566	2.048476	2.774019	2.927332	2.855797	2.75681549	2.611463
Province: Fars									
Javim	8.421816	8.744318	8.653303	0.450295	0.504854	0.588539	4.625315	4.55453769	4.40316
Marvdasht	6.646593	7.357373	7.177951	1.742969	1.953834	2.080937	2.77365	2.75681549	2.650937
Abade	7.173806	7.804519	8.036607	3.318574	3.713614	3.855569	2.013031	1.97554678	1.971285
Eghlid	9.616124	10.95201	11.0366	1.548799	1.349013	1.508229	3.410029	3.74061469	3.603215
Province: Kerman									
Arzooye	6.933898	7.279421	7.153152	2.03767	2.273895	2.351571	2.621186	2.53922029	2.48472
Rafsanjan	7.311908	8.009118	8.491445	3.907866	4.246056	4.35882	1.821892	1.83253161	1.866707
Shahre Babak	6.913224	7.813935	8.121012	2.357432	2.525869	2.650656	2.421381	2.49322671	2.474196
Province: Golestan									
Agh Ghala	6.190635	6.883584	7.193424	1.956353	2.687617	2.850234	2.523636	2.23960149	2.250729
Marave Tappe	7.770115	8.054037	8.157276	2.07633	2.340933	2.433518	2.748496	2.63595145	2.613885

Table 4 (*Continued*)

Parameter	U_{me}			U_{mp}			K_e		
Height Site	10 m	30 m	40 m	10 m	30 m	40 m	10 m	30 m	40 m
Province: Hormozgan									
Jask	6.696192	7.001333	7.109728	2.167997	3.015073	3.222717	2.491093	2.10843708	2.087707
Kish	7.699198	8.120798	8.493959	2.97053	3.514351	3.585885	2.255548	2.10189031	2.149081
Province: Yazd									
Behabad	7.266204	8.663994	9.826202	3.0732	2.701874	2.488619	2.132537	2.54146784	2.742985
Halvan	7.192594	8.458684	9.245523	2.502802	2.642265	2.61733	2.394205	2.53922029	2.643416
Korit	6.90099	7.844401	8.231563	1.520296	1.57321	1.607996	3.004912	3.12809261	3.151107
Abarkuh	6.46422	7.809017	8.06932	2.290716	2.369595	2.516372	2.36972	2.57816822	2.523636
Ardakan	6.96135	8.273396	8.689668	2.149034	2.178758	2.251867	2.555066	2.76800935	2.768009
Province: Sistan and Baluchistan									
Delgan	6.598907	7.861658	8.090431	1.453746	2.472163	2.547942	3.004912	2.53028322	2.566548
Dehak	9.123029	9.258792	9.124638	1.382835	1.867688	2.118633	3.486382	3.12050983	2.970876
Nosrat Abad	7.07626	8.534017	8.502671	2.455313	3.65333	3.701963	2.398035	2.11637704	2.127108
Lutak	9.518268	10.98692	11.37163	2.118832	3.579725	3.963634	2.991184	2.48260514	2.441324
Khash	8.966207	9.970244	10.13483	1.460061	1.706205	1.951814	3.396136	3.33298392	3.194365
Chabahar	7.437336	7.666983	7.749164	4.298	4.742451	4.887891	1.719305	1.63058035	1.625333
Province: Gilan									
Langrood	7.449589	6.685089	6.307067	1.349655	2.504134	2.769919	3.259855	2.29521074	2.174645
Province: Semnan									
Haddadeh	8.9954	10.2477	10.94005	2.575773	3.211786	3.409321	2.655982	2.53474117	2.552786
Kahak	6.529332	8.618754	9.322953	2.699006	3.309309	3.426079	2.16317	2.26201991	2.30202
Moalleman	9.193234	10.67836	11.0926	3.070174	3.778843	3.94551	2.44943	2.37157824	2.373441
Province: Mazandaran									
Senar	7.890652	10.75895	10.58587	0.801135	0.224186	0.316971	3.96663	5.30665615	5.058302
Province: Ghazvin									
Shurje	10.83135	12.64157	13.24039	3.171417	3.216367	3.234988	2.626084	2.81396709	2.846702
Jarandagh	10.83135	12.64157	13.24039	3.171417	3.216367	3.234988	2.626084	2.81396709	2.846702
Province: Zanjan									
Soltanye	11.94036	12.25225	12.47543	0.418179	0.713967	0.842755	4.973614	4.5458465	4.419464

from the measured data and Weibull distribution and found few differences between them.

$$\begin{aligned}&\frac{\overline{P}}{A} < 100 \quad (\mathrm{W/m^2}) \quad \text{—poor}\\&\frac{\overline{P}}{A} \approx 400 \quad (\mathrm{W/m^2}) \quad \text{—good}\\&\frac{\overline{P}}{A} > 700 \quad (\mathrm{W/m^2}) \quad \text{—great}\end{aligned} \tag{12}$$

2.6. Wind rose

A wind rose is a diagram showing the temporal distribution of wind direction and azimuthal distribution of wind speed at a given location (Fig. 7). A wind rose is a convenient tool for displaying anemometer data (wind speed and direction) for sitting analysis. This figure illustrates the most common form, which consists of several equally spaced concentric circles with 8 equally spaced radial lines (each represents a compass point). The line length is proportional to the frequency of the wind from the compass point, with the circles forming a scale. The legend of wind rose shows special colors for each wind velocity limit. The frequency of calm conditions is indicated in the center.

2.7. GIS map

Maps have been used for thousands of years, but it is only within the last few decades that there has been technology to combine maps with computer graphics and databases to create geographic information systems or GIS.

GIS uses layers, called "themes," to overlay different types of information, much as some static maps use Mylar overlays to add tiers of information to a geographic background. Each theme represents a category of information, such as roads or forest cover. As with the old Mylar maps, the layers which are underneath remain visible while additional themes are placed above. The themes in the above graphic are only a small example of the wide array of information that can be viewed or analyzed with a GIS. GIS themes are shown in Fig. 8.

GIS is all about spatial data and the tools for managing, compiling, and analyzing that data.

Elevation, temperature, and contamination concentrations are type of data that can be represented by surface in GIS maps. Each raster cell represents a measurement such as a cell's relationship to a fixed point or specific concentration level. Because obtaining values for each cell in a raster is typically not practical, sample points are used to derive the intervening values using the interpolation tools in ArcGIS Spatial Analyst. Therefore, the ArcGIS Spatial Analyst extension provides tools for spatial data analysis that apply statistical theory and techniques to the modeling of spatially referenced data.

A set of sample points representing changes in landscape, population, or environment can be used to visualize the continuity and variability of observed data across a surface through the use of interpolation tools. These changes can be extrapolated across geographic space. The morphology and characteristics of these changes can be described. The ability to create surfaces from sample data makes interpolation both powerful and useful.

2.7.1. Interpolation methods

To create a surface grid in ArcGIS, the Spatial Analyst extension employs one of several interpolation tools. Interpolation is a procedure used to predict the values of cells at location that lack sampled points. It is based on the principle of spatial autocorrelation or spatial dependence, which measures degree of relationship/dependence between near and distant objects.

Table 5
Standard deviation, annual direction and surface roughness length for sites.

Parameter	Standard deviation			Annual direction		Z_0 (mm)
Height\Site	10 m	30 m	40 m	30 m	37.5 m	
Province: Ardabil						
Meshkin Shahr	3.414597	3.824251	3.630982	178.4516	180.2745	2.13E−05
Namin	3.801439	4.312516	4.549626	152.7102	157.0497	3.15
Province: East Azarbaijan						
Oscoo	3.017245	3.399323	3.462821	185.452	205.3308	1.59E−03
Ahar	4.85969	4.97103	5.099521	146.3561	148.3609	2.20E−11
Bonab	2.344537	2.794405	2.955916	175.3589	183.6951	65.6
Mayan	2.605432	3.220557	3.428171	134.2027	135.2678	98.9
Province: West Azarbaijan						
Chaldoran	3.030449	3.216798	3.278548	189.964	190.2162	1.74E−02
Province: Isfahan						
Brojen	2.726368	3.174405	3.397556	187.4304	188.3738	3.54
Moghar	2.217262	2.686303	2.857128	205.74	206.9095	53.7
Morchekhort	2.271155	2.647887	2.825296	193.2988	190.6852	34.3
Varzaneh	2.718768	3.42813	3.467564	184.8529	179.8076	13.6
Province: Tehran						
Eshtehard	3.002326	3.304368	3.507255	200.191	224.7605	14.3
Kahrizak	2.185289	2.726713	2.722899	209.4047	232.476	328
Latman	2.367574	2.734855	3.042797	195.3565	199.3106	8.35E−03
Province: Markazi						
Khomeyn	2.383731	2.915642	3.010266	183.1318	170.8909	4.94
Province: Hamedan						
Nahavand	2.133073	2.406763	2.991294	195.5273	160.978	13.9
Rasul Abad	3.052498	3.603964	3.820904	120.0513	200.574	1.65
Kabodarahang	2.712011	3.151847	3.317351	148.3911	194.0343	1.12
Province: Bushehr						
Delvar	2.178304	2.417607	2.517699	186.967	196.4606	57.4
Bardkhoon	2.671862	3.005878	3.272652	177.0295	192.9026	64.2
Province: North Khorasan						
Esfarayen	2.335992	2.888378	3.041675	130.6441	137.1297	25.25
Bojnurd	3.267637	3.439764	3.512614	157.5892	162.8801	4.34E−02
Province: RazaviKhorasan						
Davarzan	2.291254	2.875509	3.076008	180.7697	185.5008	73.2
Sarakhs	2.497266	2.892963	3.006505	158.1967	216.5702	56.4
Ghadamgah	3.187442	3.945111	4.100367	204.8267	221.2494	40.6
Khaf	5.832633	6.638595	6.75596	104.2996	90.03272	3.21
Jangal	2.015147	2.425908	2.611727	251.1717	225.1001	52.3
Rudab	3.009375	3.805186	3.994996	120.8755	129.6836	42.7
Afriz	3.285234	3.922937	4.013947	140.3505	140.8267	15.4
Province: South Khorasan						
Fadashk	2.839558	3.210063	3.28446	274.7174	276.0107	13.4
Nehbandan	3.802163	4.315682	4.47139	169.215	166.276	1.65
Province: Kermanshah						
Mahi Dasht	2.105349	2.533336	2.712739	188.3126	176.8273	54.0
Province: Kordestan						
Divandare	2.818891	3.151338	3.060255	180.2234	173.1203	21.2
Ghorveh	3.110185	3.80044	3.952893	217.8756	217.3085	0.321
Province: Khuzestan						
Abadan	2.270789	2.419184	2.596558	246.3065	230.1449	227.4
Shushtar	1.596196	2.15097	2.401104	220.2049	221.9591	834
Mahshahr	2.277837	1.463364	2.798421	247.3471	248.3555	2.30E−01
Hoseynie	2.808174	3.483406	3.302516	184.0595	183.6083	70.0
Province: Fars						
Javim	1.781184	2.099424	2.206346	184.7866	182.2879	43.3
Marvdasht	1.95904	2.218728	2.25471	184.7153	192.6245	4.43
Abade	2.469863	2.773771	2.884484	194.7249	191.9417	5.51
Eghlid	3.329663	3.880323	3.953191	209.8125	213.8054	0.889
Province: Kerman						
Arzooye	2.147257	2.302018	2.316352	162.8592	160.1942	7.91E−02
Rafsanjan	2.210512	2.581215	2.756651	223.7448	213.9056	14.8
Shahre Babak	2.256268	2.677407	2.775314	184.5868	178.0578	13.5
Province: Golestan						
Agh Ghala	1.942777	2.220881	2.378029	197.4689	182.4397	129
Marave Tappe	2.421004	2.606717	2.686701	149.3332	209.9969	5.21E−01

Table 5 (*Continued*)

Parameter	Standard deviation			Annual direction		Z_0 (mm)
Height\Site	10 m	30 m	40 m	30 m	37.5 m	
Province: Hormozgan						
Jask	2.09076	2.25426	2.392495	171.1304	174.6775	86.3
Kish	2.619048	2.758898	2.979691	221.6385	132.293	2.26
Province: Yazd						
Behabad	2.360814	2.864074	3.12452	196.4538	200.2936	1.33E−02
Halvan	2.446944	2.93416	3.128591	176.0196	163.8009	8.23
Korit	2.098913	2.520198	2.678709	205.2341	199.642	26.3
Abarkuh	2.103361	2.619295	2.767279	169.7016	162.85	35.5
Ardakan	2.289256	2.836568	2.992076	149.613	152.6052	27.7
Province: Gilan						
Langrood	2.156823	2.188887	2.206624	188.5807	188.5537	147
Province: Sistan and Baluchistan						
Delgan	2.203512	2.687509	2.937481	179.5698	180.4591	494
Dehak	2.883196	3.151219	3.228846	174.9027	173.8639	158
Nosrat Abad	2.627245	2.755182	2.86914	182.4217	179.8559	7.29
Lutak	3.463744	4.159939	4.433903	252.8872	249.1792	455
Khash	2.932186	3.302589	3.41601	204.9622	196.7665	7.43
Chabahar	2.306188	2.358698	2.443786	187.7183	190.108	9.10E−02
Province: Semnan						
Haddadeh	3.127457	3.548523	3.820151	240.589	110.717	29.5
Kahak	2.094946	2.736472	2.961223	154.1383	138.82	175
Moalleman	3.129261	3.609805	3.827895	184.9128	183.9796	31.8
Province: Mazandaran						
Senar	1.97424	2.394118	2.413162	133.2636	134.6791	1.75E−03
Province: Ghazvin						
Shurje	3.954705	4.725494	4.905339	159.3075	157.8248	4.70
Jarandagh	3.954705	4.725494	4.905339	159.3075	157.8248	4.70
Province: Zanjan						
Soltanye	3.223641	3.88765	4.040272	163.9975	163.702	133

Spatial autocorrelation determines if values are interrelated. If values are interrelated, it determines if there is a spatial pattern. This correlation is used to measure

- Similarity of objects within an area.
- The degree to which a spatial phenomenon is correlated to itself in space.
- The level of interdependence between the variables.
- Nature and strength of interdependence.

There are two categories of interpolation techniques: deterministic and geostatistical. Deterministic interpolation techniques create surfaces based on measured points or mathematical formulas. Methods such as Inverse Distance Weight (IDW) are based on the extent of similarity of cells while methods such as Trend fit a smooth surface defined by a mathematical function. Geostatistical interpolation techniques such as Kriging are based on statistics and are used for more advanced prediction surface modeling that also includes some measure of the certainty or accuracy of predictions.

The IDW function is used when the set of points is dense enough to capture the extent of local surface variation needed for analysis; therefore, it was used in this study. IDW determines cell values using a linear-weighted combination set of sample points. The weight assigned is a function of the distance, the less influence the cell has on the output value [20]. For more study, refer to [21–23].

2.7.2. GIS maps of Iran

The wind roses showed the frequency of wind in different directions for each available site. It must be noted that the comparison between the wind roses is very difficult, because the number of sites are many and cannot be shown and compared simultaneously. For a better decision on feasibility study of wind, and due to above mentioned advantages, GIS maps are used in this research.

Whereas the wind data for all of relevant potential locations is not available, interpolation was used for wind speed data and also wind power densities to estimate the potential of wind energy in locations have no data.

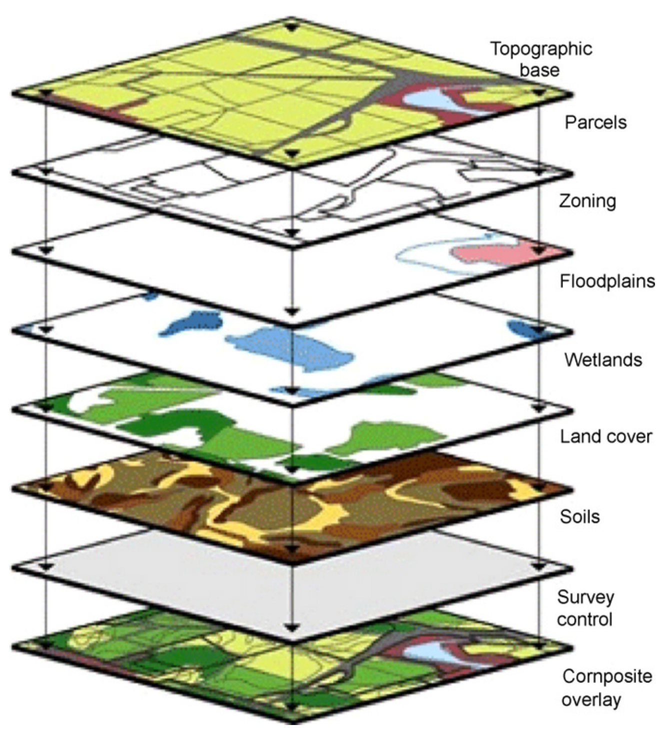


Fig. 8. GIS themes [19].

Table 6
Probability of wind speed $P(U > 5\,\mathrm{m/s})$ and annual power density.

Parameter	$P_{(\text{measurement data})}$			$P_{(\text{Weibull distribution})}$			$P(U > 5\,\mathrm{m/s})$		
Height Site	10 m	30 m	40 m	10 m	30 m	40 m	10 m	30 m	40 m
Province: Ardabil									
Meshkin Shahr	270.7607	320.5541	333.1809	215.3848	273.6053	152.977	0.336032	0.3416	0.291387
Namin	170.1754	239.162	275.9291	276.7446	341.2711	375.1958	0.346507	0.3721	0.380806
Province: East Azarbaijan									
Oscoo	176.3673	226.5128	235.0597	153.1018	192.9918	197.9794	0.398315	0.4248	0.425622
Ahar	698.6162	705.2253	783.0581	446.8664	412.8114	428.9865	0.578499	0.5559	0.563546
Bonab	59.60175	101.0606	119.2245	87.26965	127.8062	150.6364	0.244586	0.3118	0.338916
Mayan	108.3954	188.5003	223.3875	116.9848	223.9235	258.3447	0.345665	0.4747	0.498476
Province: West Azarbaijan									
Chaldoran	122.8818	151.8705	163.4584	157.207	174.4522	172.2503	0.295011	0.3169	0.315844
Province: Isfahan									
Brojen	62.14171	94.43281	113.0276	155.6033	195.3081	234.5208	0.286931	0.3073	0.323802
Moghar	54.98424	106.9535	135.4195	73.13773	113.2406	125.7507	0.247252	0.3279	0.346861
Morchekhort	65.59128	114.4081	143.0571	75.95441	113.9179	131.9546	0.265503	0.3526	0.381435
Varzaneh	107.6252	180.5306	218.5603	111.6105	164.1679	182.5752	0.320691	0.3724	0.386903
Province: Tehran									
Eshtehard	186.0952	267.7968	317.5525	134.2974	179.7955	209.0515	0.372576	0.4507	0.480278
Kahrizak	48.86963	104.7237	120.9691	87.1348	134.6778	157.5348	0.250056	0.3466	0.390633
Latman	95.91749	126.7095	160.247	90.51447	122.5378	152.6312	0.312911	0.3527	0.371331
Province: Markazi									
Khomeyn	62.89948	97.25482	105.307	91.65224	148.9836	160.8585	0.261117	0.3208	0.332617
Province: Hamedan									
Nahavand	96.0315	102.37	111.1	99.77639	106.6581	185.9131	0.229014	0.2427	0.267361
Rasul Abad	104.6472	151.7221	171.6661	179.4061	254.8279	300.2806	0.34639	0.3808	0.394378
Kabodarahang	108.7	154.18	168.15	108.8706	155.8343	170.647	0.302534	0.3517	0.362915
Province: Bushehr									
Delvar	61.35495	93.71103	107.1111	58.25334	90.48183	104.9673	0.203548	0.3031	0.338789
Bardkhoon	132.8538	203.4669	258.4392	125.1229	195.8355	252.5269	0.375249	0.4938	0.546588
Province: North Khorasan									
Esfarayen	71.04055	116.5007	135.1934	82.46056	142.1227	150.0036	0.263663	0.3513	0.355266
Bojnurd	168.0389	206.382	229.4657	260.6792	287.2761	295.2027	0.479385	0.5089	0.521466
Province: RazaviKhorasan									
Davarzan	78.94886	134.1602	160.7935	67.45472	108.5624	120.8128	0.215218	0.2861	0.300033
Sarakhs	98.16197	159.0453	178.2521	106.2976	137.4418	150.0637	0.309738	0.3747	0.393674
Ghadamgah	143.6632	247.9569	273.8541	150.2177	234.5695	255.2919	0.324594	0.3849	0.397999
Khaf	1579.319	2298.165	2512.037	1188.785	1783.686	2040.226	0.734452	0.7785	0.800516
Jangal	65.0435	107.4246	129.2318	71.7728	128.6571	151.542	0.278753	0.4164	0.448026
Rudab	168.8913	293.6769	324.5605	128.9334	244.8169	273.1627	0.374211	0.4834	0.497199
Afriz	149.7988	221.1019	236.8871	243.689	325.7413	339.8605	0.417613	0.4568	0.468654
Province: South Khorasan									
Fadashk	177.7125	274.8891	291.6576	177.6438	276.9668	294.7942	0.489148	0.6031	0.614804
Nehbandan	256.618	411.5948	411.5948	256.6791	372.9285	411.663	0.415255	0.4709	0.484193
Province: Kermanshah									
Mahi Dasht	46.41831	77.89169	95.25264	74.1278	134.7195	116.7612	0.217143	0.3079	0.28605
Province: Kordestan									
Divandare	91.40244	148.4143	131.4898	141.5868	176.8592	163.669	0.304613	0.3803	0.356003
Ghorve	140.4844	203.3116	224.5564	163.0886	256.9803	275.3581	0.354152	0.3857	0.393234
Province: Khuzestan									
Abadan	88.37591	138.8743	195.8197	85.97388	138.5177	205.1595	0.308579	0.4655	0.596259
Shushtar	18.84883	48.59023	66.44708	47.76053	79.94448	96.18509	0.156751	0.2417	0.272761
Mahshahr	108.9596	99.91551	249.628	93.49095	146.9809	245.1192	0.347418	0.5075	0.640208
Hoseynie	110.1144	188.6736	181.0384	124.8712	254.0722	223.5687	0.320681	0.4562	0.448222
Province: Fars									
Javim	77.52603	95.90944	98.14388	95.46647	107.8928	109.1451	0.210775	0.2278	0.233344
Marvdasht	27.0675	45.35511	50.41678	65.1863	88.77515	86.84241	0.213754	0.2668	0.268905
Abade	119.1217	188.814	217.7209	102.2845	133.5081	148.2117	0.355891	0.4235	0.448605
Eghlid	145.786	205.7927	223.2192	172.407	240.0233	244.598	0.340036	0.3727	0.383627
Province: Kerman									
Arzooye	50.2826	65.97104	70.63205	76.86897	90.87401	90.31513	0.248773	0.2842	0.286721
Rafsanjan	114.4616	171.7102	197.1043	116.5411	152.493	175.8682	0.415241	0.4807	0.507946
Shahre Babak	72.6017	113.9428	129.2985	80.4018	113.8034	126.707	0.2687	0.3307	0.353316
Province: Golestan									
Agh Ghala	43.89711	71.29008	84.43408	56.12676	83.77728	102.0879	0.198533	0.2898	0.330165
Marave Tappe	65.91005	87.38907	97.03923	104.7808	120.0097	129.0562	0.296586	0.3293	0.344753

Table 6 (*Continued*)

Parameter	$P_{(\text{measurement data})}$			$P_{(\text{Weibull distribution})}$			$P(U>5\,\text{m/s})$		
Height Site	10 m	30 m	40 m	10 m	30 m	40 m	10 m	30 m	40 m
Province: Hormozgan									
Jask	53.58448	85.01534	103.1021	71.66102	91.98144	107.9684	0.24305	0.3214	0.359439
Kish	126.6977	174.8383	211.6776	116.6452	143.8517	167.2399	0.357792	0.4219	0.448116
Province: Yazd									
Behabad	101.99	153	178.4341	101.9946	153.1239	178.4341	0.341763	0.3838	0.393784
Halvan	91.21	142.37	169.76	91.25269	142.5797	170.2362	0.295225	0.3703	0.394229
Korit	64.55	92.81	104.08	69.19349	98.98571	110.9157	0.214396	0.2658	0.283105
Abarkuh	66.713	111.035	119.44	66.71296	111.035	119.4408	0.23625	0.3192	0.337488
Ardakan	79.14	125.888	138.986	79.14031	125.8926	138.9958	0.257642	0.3283	0.346204
Province: Sistan and Baluchistan									
Delgan		118.744	147.5418	60.49886	114.7442	134.9142	0.193988	0.3292	0.357216
Dehak	96.68779	141.5606	162.1684	145.1355	163.0216	174.6203	0.308714	0.3488	0.371203
Nosratabad		147.9597	170.6332	86.80071	166.134	176.4384	0.285117	0.4515	0.46288
Lutak	196.7797	416.2597	496.3372	182.1014	317.276	397.3038	0.376928	0.5277	0.572993
Khash	103.5885	138.0427	159.9013	140.1283	195.0241	217.2538	0.30785	0.3646	0.391709
Chabahar	117.2751	151.6958	175.4865	128.1525	146.3095	158.6649	0.459659	0.5166	0.539909
Province: Gilan									
Langrood	43.12387	69.55276	74.19055	82.53081	75.43657	80.95081	0.231753	0.2645	0.287754
Province: Semnan									
Haddadeh	146.1237	217.1086	266.0389	166.351	253.83	314.573	0.388746	0.4804	0.517192
Kahak	73.26	163.3	195.76	73.26222	163.3037	195.7569	0.267571	0.4277	0.459673
Moalleman	187.5875	300.5666	343.3564	187.5875	300.5666	343.3564	0.43297	0.5331	0.557085
Province: Mazandaran									
Senar	29.48056	46.71039	51.90701	86.47931	182.7821	159.7409	0.215156	0.2737	0.263689
Province: Ghazvin									
Shurje	324.0052	498.6489	550.5248	292.631	444.211	482.8363	0.49549	0.545	0.554754
Jarandagh	216.0517	332.5069	367.0985	292.631	444.211	482.8363	0.49549	0.545	0.554754
Province: Zanjan									
Soltanye	253.075	287.73	324.65	260.0628	297.1536	335.8605	0.329361	0.364	0.386765

In this work we plot six GIS maps for Iran, about U_{average} and power density of measurement data in three heights. These contours have a scale of 1:10,000,000. GIS maps have been shown in Figs. 9–14. There are different colors in GIS map that indicate the quantity of wind speed and power density on each location. On the other hands, the different ranges of wind speed and power density can be shown by colors. If the location has the better condition, its color is near to red. Also the location with the low wind speed and power density is displayed by green color.

As indicated in the maps, the eastern and northwestern regions of Iran have a good potential for installing wind turbines for capturing the. These regions situated in the path of strong wind flows. The

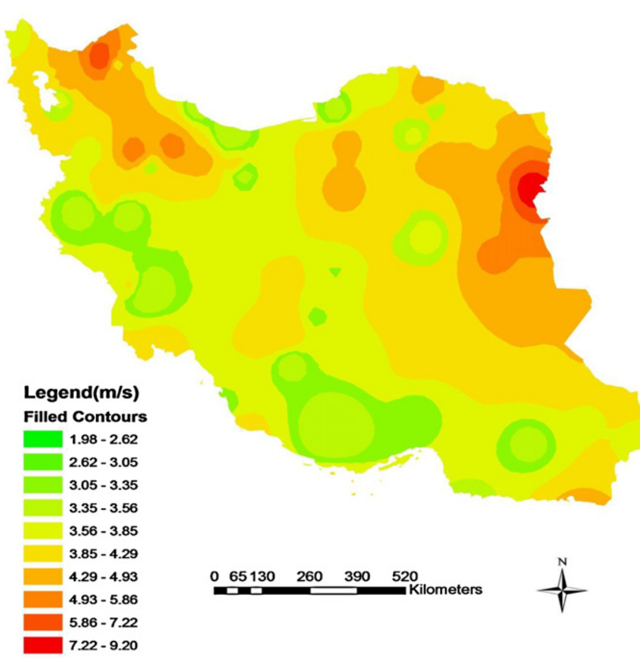


Fig. 9. GIS map of U_{average} in 10 m.

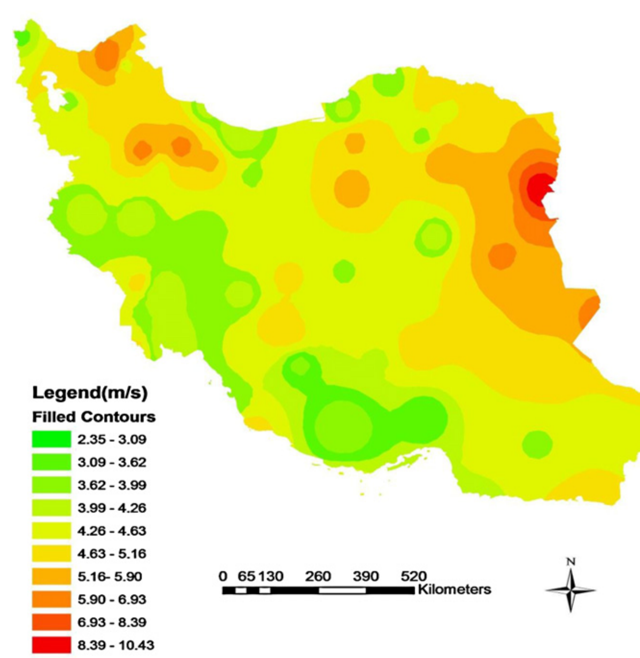


Fig. 10. GIS map of U_{average} in 30 m.

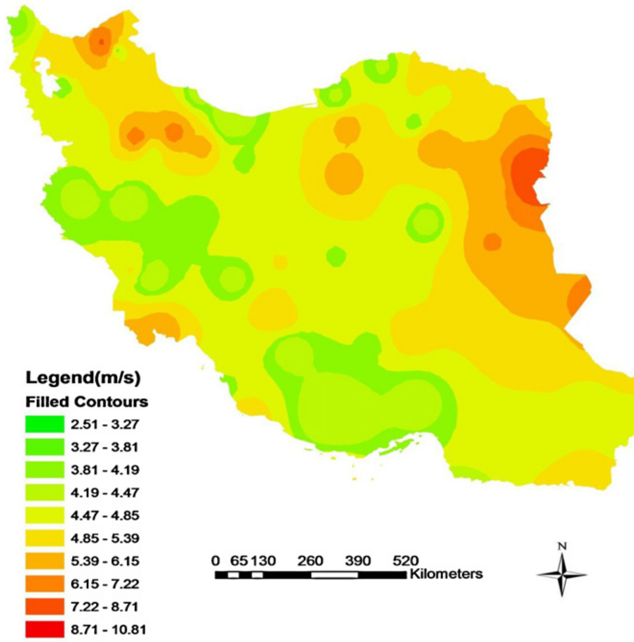


Fig. 11. GIS map of U_{average} in 40 m.

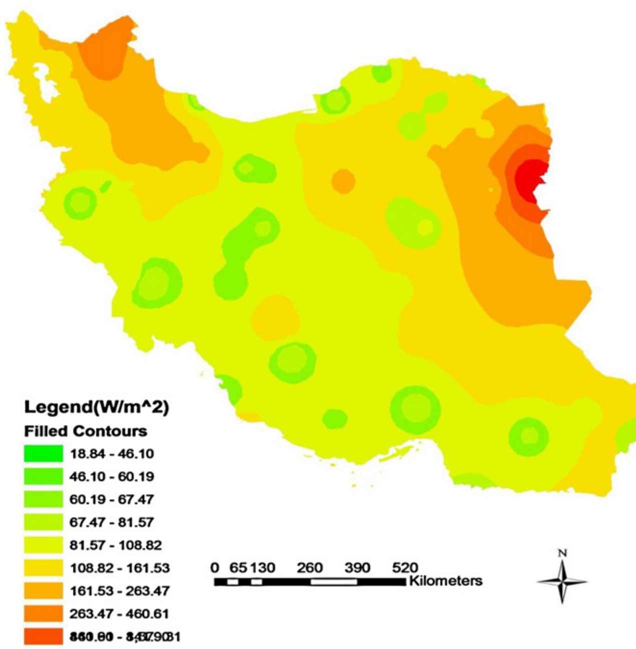


Fig. 12. GIS map of $P_{(\text{measurement data})}$ in 10 m.

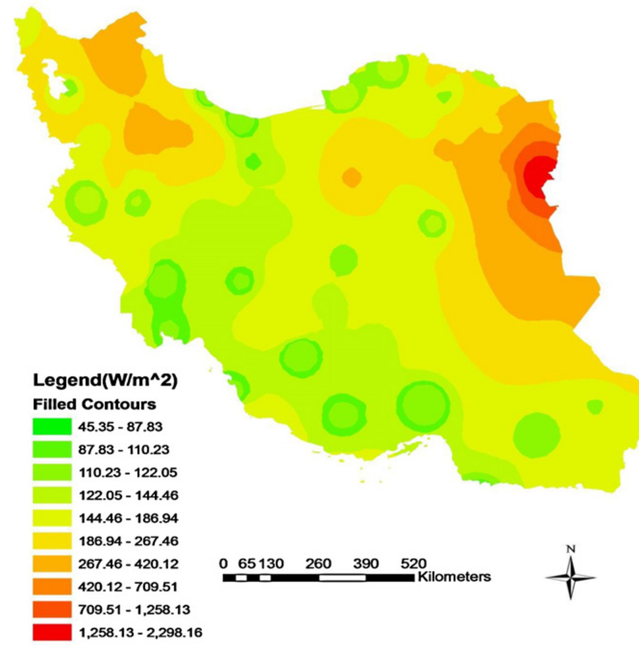


Fig. 13. GIS map of $P_{(\text{measurement data})}$ in 30 m.

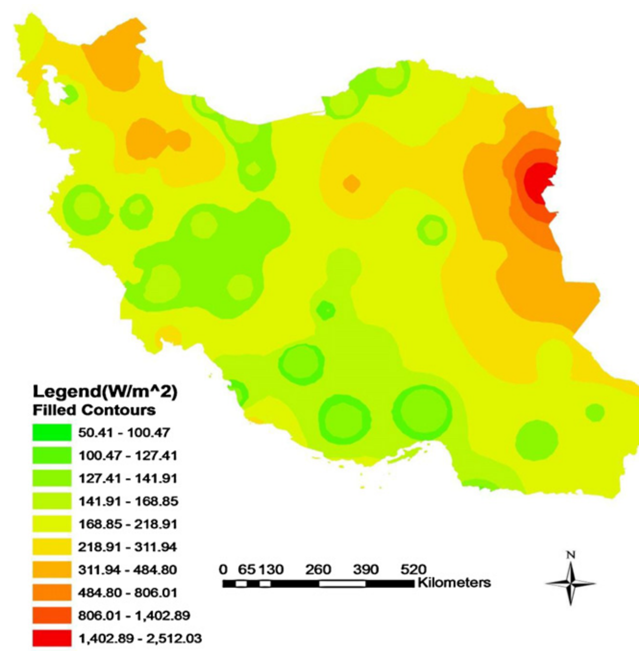


Fig. 14. GIS map of $P_{(\text{measurement data})}$ in 40 m.

central and southern regions of Iran do not have a relevant potential as it can be seen in these maps. Also, some of these regions are suitable for installing wind turbines to pump water.

It must be noted, all sites that have a good condition in wind potential have a good power density. ArcGIS can be used to find proper places for installing wind turbines considering the effects of other factors, like the distance from cities, roads, etc. Whereas SUNA has considered these factors in installing its meteorological sites, ArcGIS is just applied for interpolating data from 68 mentioned sites.

3. Conclusion

A detailed statistical study of wind at 10 m, 30 m and 40 m heights in Iranian cities was presented. The data used in the study was collected by Renewable Energies Organization of Iran (SUNA).

Wind speed frequencies were approximated using Weibull probability function. The Weibull parameters k (dimensionless) and c (m/s) were shown in Table 3. Energy pattern factor, U_{me}, U_{mp}, standard deviation, annual direction, surface roughness length, probability of wind speed $P\,(U > 5\text{ m/s})$, annual power density, wind rose and GIS maps for sites were recorded and presented.

It must be noted that the comparison between the wind roses is very difficult, because the number of sites are many and cannot be shown and compared simultaneously. For a better decision on feasibility study of wind, and due to above mentioned advantages of GIS, the GIS maps are used in this research.

ArcGIS can be used to find proper places for installing wind turbines considering the effects of other factors, like the distance from cities, roads, etc. Whereas SUNA has considered these factors in installing its meteorological sites, ArcGIS is just applied for interpolating data of 68 mentioned sites.

As indicated in the maps, the eastern and northwestern regions of Iran have a good potential for installing wind turbines for capturing the electric power. These regions situated in the path of strong wind flows. The central and southern regions of Iran don't have a relevant potential as it can be seen in these maps. Also, some of these regions are suitable for installing wind turbines to pump water.

Also in this work we studied a large number of sites in order to assess the wind energy in Iran. So this work can be used as a primary assessment for installing the wind farms which it can be used as a reference study.

An evaluation of the wind resource in these sites can be done, regarding wind power density classes published by U.S. department of Energy [18].

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